Critiques of Life Cycle Assessment

A Major Qualifying Project
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by

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Abstract

Following the comprehensive project, ‘A Solar Decathlon Materials Selection Study’, learning about Life Cycle Assessment (LCA) and its applications, this composition looks into the limitations of LCA. Based upon critiques of LCA from both industry professionals and academic researchers, the analysis is presented in a format following ISO (International Organization for Standardization) 14040 framework.

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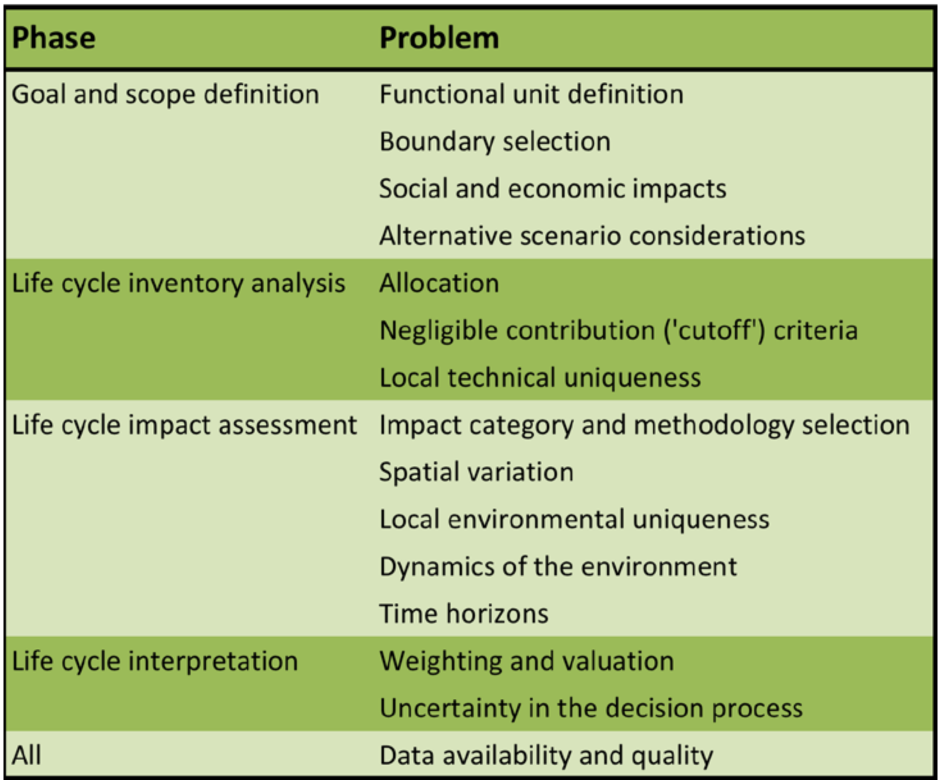
In addition, I would like to thank this project’s advisor, Professor Robert Krueger for his guidance and motivation. He inspired me to look further into the area of environmental sustainability, specifically in product and process analysis.

Executive Summary

Life Cycle Assessment (LCA) is a process used to track the environmental impact of a product or process. Many projects utilize software or practitioners who perform these analyses. The results of such studies are then used to make decisions or justify decisions that have important implications. The 4 phase process as broken down by the International Organization for Standardization (ISO) is presented in Table 1. Problems associated with each phase are also listed in this table.

Table 1: LCA Problems by Phase



Phase	Problem
Goal and scope definition	Functional unit definition
	Boundary selection
	Social and economic impacts
	Alternative scenario considerations
Life cycle inventory analysis	Allocation
	Negligible contribution ('cutoff') criteria
	Local technical uniqueness
Life cycle impact assessment	Impact category and methodology selection
	Spatial variation
	Local environmental uniqueness
	Dynamics of the environment
	Time horizons
Life cycle interpretation	Weighting and valuation
	Uncertainty in the decision process
All	Data availability and quality

This report serves to educate and present the shortcomings of a LCA analysis so that a false sense of confidence isn't used to make an important decision. Research of articles and journal entries from industry professionals provided the extensive analysis of LCA critiques and recommendations. This is not meant to transgress LCA but rather to educate software users of the assumptions and truncations that are typically performed without notice.

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Introduction

The advantages of impact assessment and Life Cycle Assessment (LCA) have been highly documented based on the amount of published academia in the recent years. This recent approach towards tracking the environmental impact of a specific product or process has been manipulated to better suit each and every need. As a result there are a few popular variations of LCA. There are problems that come with trying to conduct a LCA and this piece will lay out these problems as identified by professionals.

Limitations and Critiques

LCA is a tool in need of improvement. An improvement in the quality of data is the most in need because it impacts all four phases/stages of the process. The first stage sets study parameters, followed by the second that is primarily analysis. Finding and setting modeling parameters plagues this second phase. Boundary selection requires decisions about including and excluding processes. But, the exclusion of social or economic impacts in LCA can limit the potential of the results. During the interpretation phase, alternative scenarios and their feasibility can influence decisions. Flows and transformations during inventory analysis is a source for problems too. The attempt to accurately associate flows from multi-functional processes to each of its functions during the allocation phase produces difficulties. Local technical uniqueness is problematic when generic data is used to represent an entirety of a process. The following four sections, broken up by stage, explain uncertainty which ultimately leads to a lack of confidence in results.

Stage 1: Goal and Scope Definition

In this phase of an LCA, problems occur from methodological choices. Generally, this is the conscious decision to either include or omit certain information related to a product system. The objective of an LCA must be defined early in the effort. Social and economic impacts, although not directly quantified, are influential to an LCA. A sustainability study that does not include economic and social impacts may have decreased accuracy. A purely environmental study is not dependent on life cycle costing or a social life cycle assessment. No matter how technically advanced a study may become, the ability to make socially influenced decisions must be retained.

Functional unit definition

According to the International Organization for Standardization (ISO) “a functional unit is a measure of the performance of the functional outputs of the product system” (ISO 1997). It is crucial to establish a functional unit during the first phase to compare LCA results. Not only does a product have a function, or a use, but it may have several sub-functions which are often ignored. An unrealistic study can result from error and misunderstanding of this separation. Units are then assigned to corresponding functions. Functional comparisons need to be strict so that their units are as regular as possible. When a function is not quantifiable, it needs to be noted and adjusted for, as best possible (Cooper 2003). Lastly, when a reference flow is defined, uncertainties can stem from indeterminate product use scenarios such as a product’s lifetime or performance.

Unit process boundary selection

The selection of a study’s boundaries is also conducted in the first stage. This sets the range of processes and activities that will be included in the LCA. A boundary selection is different for all products because of the variety of life cycle stages, impacted geographic area, and relevant time horizon. Ideally, a large and detailed study with wide boundaries would be chosen, but this is not feasible with time, resource, and financial constraints. There must be a balance that understands resource limits but still sparks confidence in the LCA study. Not selecting appropriate boundaries may mean the LCA (1) does not reflect reality well enough and lead to incorrect interpretations and comparisons or (2) provide the perception to the decision maker that it does not reflect reality well enough, thus lowering his/her confidence in a decision (Graedel 1998; Lee et al. 1995). Frameworks for justifying cutoffs to a study are specified in ISO 14041. This document is highly criticized by the industry. Various researchers have argued that “a cutoff is very difficult to justify even when using ISO’s criteria” (Raynolds et al. 2000a). In addition to there being a lack of confidence in boundary selection, the ability to practice using the procedure sometimes proves difficult. A LCA practitioner may not possess the perfect knowledge of a product to predict and apply impacts of the product system.

Life cycle costs and social impacts

As previously mentioned, not only do product systems impact the environment, but they cause economic and social impacts. Some researchers have noted that, "…recommendations based on LCA fail to address possible trade-offs between environmental protection and both social and economic concerns in the product life cycle" (Dreyer et al. 2006). Ultimately, LCA results are used to make decisions. Because results impact a narrow audience, capability is reduced and has the potential to be improperly used. Life cycle costing (LCC) has proven difficult to combine with LCA, and when social impacts are attempted to be considered, difficulties halt this integration.

Alternative scenario consideration

Advantages and disadvantages of a proposed change are weighed out following analysis of LCA results. Alternative scenarios are a useful way to compare processes such as end-of-life scenarios. To perform this is to predict what the future may be like for each of the alternatives. According to one researcher "LCA studies usually do not consider the 'zero' or null alternative" (Hauschild and Wenzel 2000). Null alternatives are the scenarios that are regular or indifferent to the current practice. It is important to consider these as to define a baseline and aid in the comparison of alternatives and their corresponding advantages and disadvantages.

Stage 2: Life Cycle Inventory Analysis

Material flow, energy flow, and process modeling are problems correlated with inventory analysis. Often, deemed unimportant, is "the criteria used to identify and eliminate unimportant resource and waste flows to and from an activity…" (Reap et al. 2008).

Allocation

Allocation is among the most controversial issues of LCA. Allocation in this context means the proper distribution of environmental burdens stemming from a product or process's multiple sub-functions. Allocations made without proper knowledge could lead to incorrect LCA results, affecting decision making. Procedures for allocation have been made by ISO and a large number of practitioners but none serve to provide a general solution. As seen in the 'Recommendations & Resolutions' section of this paper, many have tried to suggest allocation procedures. But, some problems have stemmed from the subdivision and system expansion suggestions. Subdividing can be beneficial if the sub-processes are physically and economically independent of each other. Results are inaccurate in the common occurrence that this does not happen (Ekvall and Finnveden 2001). There are two popular system expansion approaches: direct system enlargement, and the avoided burdens approach. Curran does suggest that system expansion is the preferred approach towards dealing with allocation problems, but it leads to a larger model. A larger model in turn requires more data. Doing this is risky but often required to complete an LCA in a timely manner. Truncating a model threatens to discard environmental burdens that could affect the decision making process.

Negligible contribution criteria

A negligible contribution criterion is when an activity within the boundaries set during Stage 1 is deemed unimportant. This criteria can be called 'cutoff' criteria. The issue this potentially causes, is an exclusion of a process which may have been a deciding factor for results.

Local technical uniqueness

Based on a product's location, the extraction, production, distribution, and end-of-life technologies can be vastly different. Technical uniqueness affects waste emission, as well as the types and quantities of resources demanded for a product. The order of magnitude of these differences is variable as the process of a production line can vary with one across the world or even across the warehouse. Often ignored, these local uniqueness issues reduce accuracy of a process inventory.

Stage 3: Life Cycle Impact Assessment

This stage which seeks to translate burdens into environmental burdens is the most challenging of LCA's four phases because of its susceptibility to problems. The main problems in a life cycle impact assessment (LCIA) stem from attempting to connect burdens with the proper impacts at the precise time and place. Impact category selection, spatial variation, local uniqueness, environmental dynamics, and decision time horizons are discussed in this stage.

Impact category selection

Selecting impact categories and their corresponding indicators and models is one area of concern in Stage 3. There are various impact modeling approaches, but the main two are midpoint and endpoint. Midpoint modeling is a comprehensive and well defined method. Endpoint or damage impact categories lack these important features. The reason why endpoint is popular is because it is more relevant for decision making because it deals directly with the endpoint impact. As a result of these diverse approaches, different organizations have proposed different impact lists (Finnveden 2000). The main reason for this issue is a lack of current standardization in LCA literature (Udo de Haes et al. 2002). In addition to spawning differing impact lists, absence of standardization leads to disuse and an ability to oversee important impact categories. Even if standardized, there are still concerns for errors. A lack of data to support assessments of categories, a conscious decision to avoid a category, and unintentional oversight of categories make this selection prone to errors. Ultimately, when impact category selection follows multiple approaches, it creates problems when comparing LCA studies.

Once impact categories are established, an indicator and model can be utilized to assess data. Damage indicators exist but are rarely agreed upon by practitioners. Even popular LCA methodologies such as the EPS system and Eco-indicator 99 rely on varying indicators (Finnveden 2005). As one can imagine, environmental burdens impact multiple categories. This phenomenon is known as ‘double-counting’. Double counting results from both ignorance by the user and flaws in models which are intended to automatically partition burdens (Guinee and Heijungs 1993). Less easily detectable is the software’s double counting and results from this phenomenon include magnification of a burden and potentially poor decisions based on results from the LCA study. Attempts to avoid these previously mentioned difficulties are made by using predefined LCIA methodologies. These methodologies are a part of software packages where impact category, indicator and model selection, and classification have all been predefined by the software. Benefits of these attempts are time and money savings, but the results can vary based on areas of interest when conducting the study.

Spatial variation

Spatial variation is very important to an LCA. Spatial variation refers to the differences in topography, geography, and land cover to name a few. Throughout a product's lifecycle, emissions generated may occur at a number of locations and enter various environments such as air, water, and land. Local environments also react differently to these inputs based upon their sensitivity and risk levels. These local effects require spatial data because of their uniqueness when compared to global impacts such as stratospheric ozone depletion and global warming. This is one of the most obvious limited areas of LCA. There are three categorizations of an LCA that describe the extent of space overlook. A *site-generic* LCA lacks spatial information and assumes globally homogeneous effects. A *site-dependent* LCA uses varying spatial resolutions for emission and deposition sites. And a *site-specific* assessment models individual sources and local responses (Potting and Hauschild 2006).

The RAINS model and EcoSense model are used to model LCA effects. They utilize grid squares of 150 x 150km and 50 x 50km respectively. These grid square assumptions of site uniformity can produce two to three order magnitude ranges of results as studied by Hettelingh and colleagues in their assessment of European airborne pollution (Hettelingh et al. 2005). In addition to atmospheric conditions, topographical and hydrological conditions influence impacts. For example, Hellweg notes that groundwater contamination from landfills can vary by four orders of magnitude depending on geographic location (Hellweg 2001).

When studying spatial variation, not only is variations in physical land media important but the land use can vary, leading to inaccurate results. Land cover alterations and infrastructure present on a segment of land are typically not, but should be considered. Precipitation diversion, an infrastructure example, for agricultural, industrial, and domestic reasons can influence the hydrological cycle. Topography alterations, a land cover example, are directly related to erosion resistance. One can start to see how spatial variation is potentially a large area of error in an LCA.

Local environmental uniqueness

Local environmental uniqueness refers to differences in specific parameters that can describe a particular location such as soil pH. Differences in these parameters define a location's sensitivity to the stressors of a function, distinguishing one from another. In the example of particulate emissions, population density as a characteristic of a unique local environment has direct impacts in the pollutant exposure efficiencies (Nigge 2001a, b). A generic model that averages population would drastically underestimate this environmental factor, proving local environmental uniqueness is an important criteria to be aware of.

Dynamics of the environment

Dynamics are often not included in an LCA, as it is more of a steady-state tool (Udo de Haes 2006). Obviously this proves difficult, as industrial processes and environments are dynamic and affect impact assessment. This is such a large problem with LCA that ISO 14042 has acknowledged the impact ignoring time has on environmental impact, but has not listed the problems that are inherent in degrading an LCA relevance (ISO 2000a). The problems that develop are not as much from the absence of time adjustments, as they are from the disregard of the problems these absences cause.

Impacts of pollution, relating to time are: the timing of emission, rate of release, and time-dependent environmental processes (Owens 1997b). Sometimes, environments react differently to certain chemicals based upon whether their release is long term or short term. Environments can retain strength up until the capacity is exceeded for some chemicals but for others, they downgrade linearly with increased input. Opposite to immediate effects are delayed releases, or a historical record of buildup. Most LCA's average deposition and do not have a record of past impacts processes have had on an area.

Time horizons

Other than dynamics within a system, time is influential when an LCA software estimates the time horizon of an impact. Impacts rarely occur at a split moment, or continue their effects over an infinite period of time. To bind this, time horizons are selected as limits to 'integrate' over (Udo de Haes et al. 2002). Discussion of whether to do this and to what extent continue to plague the LCA community. Having infinite limits capture the entirety of a system's impacts, where impacts are truncated when limits are finite. Valuation within these limits is split into two categories. Implicit valuation happens when the practitioner chooses to truncate a time horizon or allow infinite limits. The other category is an explicit valuation where future impacts are condensed to a weighted value which is impacted by time. An environmental impact discount or appreciation rate is a source of controversy within the field of LCA.

Stage 4: Life Cycle Interpretation

Interpretation of results differs based upon the intent of the LCA as established in the first step of LCA. LCA's can be used to identify areas of improvement, recommend a course of action, or to identify areas to investigate in a future, more detailed LCA. Analyzing results is tedious but methodical and traceable. Decision making is quite the opposite and is not uniform anywhere along the LCA track. This is why decision making in Stage 4 as well as in Stage 1, when goal and scope were defined, are areas requiring improvement in the field of LCA. Uncertainty must be accounted for and managed.

Incorporating subjective values using weighting

To analyze the human behavior of LCA decision making, one weighs and then ranks the importance of different parts of multiple objectives. To rank such environmental impacts requires comparing values of different units and scales. This subjective approach does not lean itself toward accurate and highly reproducible results.

This challenge has been recognized, and the weighting methods developed to combat it have been studied too. Finnveden and coauthors evaluated several processes with a performance based method and concluded that not one of the weighting methods met all criteria of an author (Finnveden et al 2002). Importantly concluded was that:

> 1. It may be difficult to assure that an elicited weight accurately reflects a decision maker's value for some performance objective, particularly with respect to other performance objectives.
> 2. Weights derived through different value (or preference) elicitation methods may not be comparable, and therefore, aggregation may not be possible without hiding added assumptions.
>
> *(Finnveden et al. 2002)*

Monetization is a category of valuation stemming from environmental economics. This method uses a monetary value to quantify values of environmental impacts. A commonality to this method is that most measure willingness to pay (WTP). Who is paying, how it is measured, or what values are selected varies (Turner et al. 1993). Examples of methods can be either asking individuals directly or observing market behavior, based on the "environment's use value, nonuse value, or total economic value" (Finnveden et al. 2002). Despite sharing the same units, researchers have warned against comparing methods, especially taking all means to keep environmental and non-environmental costs separate (Bockstael et al. 2000). It has also been recommended that WTP methods not be the only method used, but if so, then regional differences and external costs should be acknowledged.

Alternative to monetization are methods developed involving normalization. Normalizing objectives to a comparable level then weighing them and aggregating results is the general overview of any of these processes. Base problems of these methods result from decision analysis and bias. Bias is split up into two categories, behavioral and procedural (Weber and Borcherding 1993). "Procedural bias can be that due to survey framing or wording or to choice of cognitive references" (Reap et al. 2008). Bias is studied to an extent because it is hard to verify whether or to what extent it has played a role in normalization. As explained above, weighting can be difficult when used to support a selection between alternatives; a better way to use this analysis would be to classify a product system as environmentally 'good' or 'bad'.

Uncertainty in the decision process

As in all scientific studies, reliability is the basis for utilizing the data for decision making. To qualify the reliability, uncertainty aspects must be considered. "Uncertainty is a lack of knowledge about the true value of a quantity, true form of a model, appropriateness of a modeling, or methodological decision, etc." (Reap et al. 2008). Uncertainty analysis is one technique which models uncertainties in the inputs of an LCA. A second analysis is a sensitivity analysis, which studies the effects of manual changes in inputs on LCA outputs. By studying the sensitivity to change of inputs, this may qualify or regulate the influence of uncertainty in the input stage. ISO's LCA series of standards mentions these two methods but fails to provide guidance of how to properly use them (ISO 2000a, b, 2006). Four categories of problems stem from uncertainty: modeling of uncertainty, incorporation of multiple uncertainties, completeness of analysis, and cost of analysis.

Probability distributions have been the most commonly used means to display uncertainty in LCA models. Despite an industry norm of using these models, the data sources and assumptions used to create them remain unexplained. To better confirm these models, sensitivity analyses can be used to overlay the results, but this adds a layer of complexity that hinders this area of LCA. When uncertainty is present, data may be used to cover up gaps. Representativeness of a model shall be an area researched to determine what data is incomplete or missing to improve a study going forward.

It is easier to decide between alternatives when uncertainties are combined and compared. This is a problematic area for LCA results. While comparing alternatives shows their specific effects on a single environment dimension, combining all the results allows for no unique analysis of their impact. This spawns a problem of how to display uncertainty. One approach is the idealistic one which has an intent to use as much available information about uncertainty and as few unwarranted assumptions about that information as possible. The other aspiration is to factor all uncertainty models, no matter how different, into an efficient, rational decision-making process (Reap et al. 2008). This desire is limited, as developing uncertainty models is harder for impact assessment than for life cycle inventory (Owens 1997). A practitioners approach to this problem can be to characterize uncertainty that is easily quantifiable, and fail to acknowledge the existence of other uncertainty. A partial analysis such as this one can generate false confidence. There are no frameworks as of 2008 that address this tradeoff.

Data Quality

Poor data quality is the main cause of uncertainty. Main types of uncertainty due to data quality are in the forms of poorly measured data (‘data inaccuracy’), data gaps, unrepresentative (proxy) data, model uncertainty, and uncertainty about LCA methodological choices (Bjorklund 2002).

General problems limiting data quality

A practitioner's uncertainty can arise after seeing that two or more data sources (measuring the same effects) have produced different numbers. To combat this, standardized databases of LCA data are idealized in an attempt to reduce the burdens of data collection, and to eliminate uncertainty. According to Vignon and Jensen, "there are few established, standardized, or consistent ways to assess and maintain data quality (Vignon and Jensen 1995).

Data quality in LCI

Inventory analysis invokes added barriers to data collection that literature has agreed are unique to life cycle inventories. Methods for data collection are inherently expensive (e.g. submetering implementation in an industrial facility, field data collection, or frequent data collection to maintain relevance) (Maurice et al. 2000). Some data is not available at a practitioner's organization. This information on production or other methods can be kept by suppliers or partners that have valid concerns about sharing inventory data that could reveal confidential information related to their competitive advantage (Ayres 1995). If this information that was not initially available to the practitioner is handed over by a third party, the accuracy, reliability, collection method, and frequency of measurements cannot be confirmed.

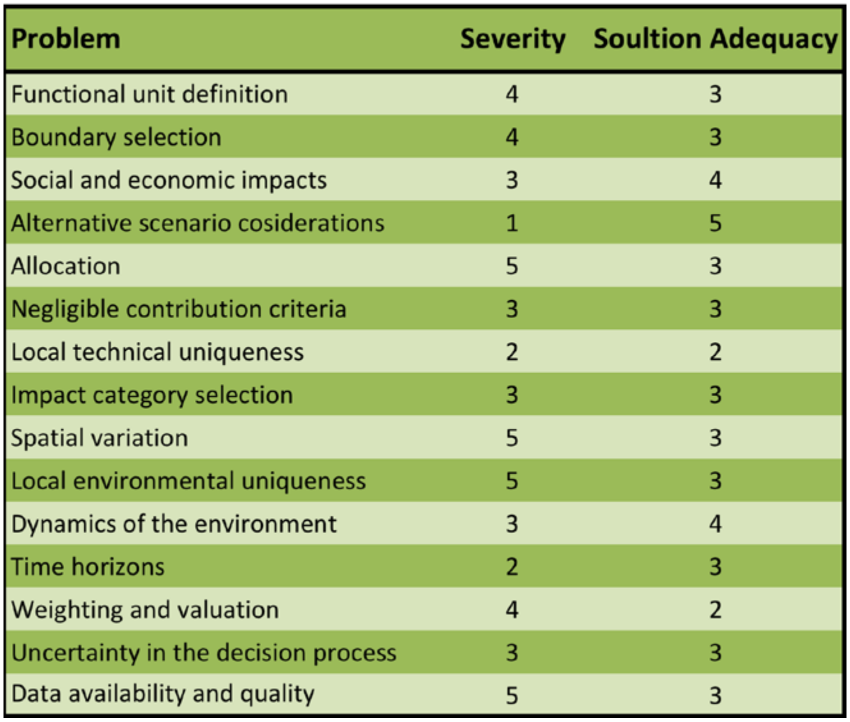
Data quality in impact assessment

The most serious data and model quality downfalls come via impact assessment. Characterization models and their corresponding environmental mechanisms, rarely line up. Thresholds of environments are not generally on file, and if so, the confidence in one is low. A threshold does not apply to a locale for an endless time period and synergistic combinations of chemicals in a common locale are irrelevant in current impact assessments (Bare et al. 1999).

Recommendations & Resolutions

As one reads this document they may become overwhelmed with which areas most affect the results of an LCA. To better frame the problems and their severity, Reap and coauthors have presented a list, which is recreated in Table 2.

Table 2: Problms in LCA qualitatively rated by severity and adequacy of current solutions (1, minimal severity while 5, severe; 1, problem solved while 5, problem largely unaddressed)



Problem	Severity	Soultion Adequacy
Functional unit definition	4	3
Boundary selection	4	3
Social and economic impacts	3	4
Alternative scenario cosiderations	1	5
Allocation	5	3
Negligible contribution criteria	3	3
Local technical uniqueness	2	2
Impact category selection	3	3
Spatial variation	5	3
Local environmental uniqueness	5	3
Dynamics of the environment	3	4
Time horizons	2	3
Weighting and valuation	4	2
Uncertainty in the decision process	3	3
Data availability and quality	5	3

For example, spatial variation problems are given a 5 because they can lead to "multiple order of magnitude differences in characterization factors" (Reap et al. 2008) for categories that are typically used in any LCA. Further development of spatially explicit, dynamic modeling is recommended to ameliorate the problem of spatial variation and local environmental uniqueness. Impact assessment is the most heavily affected by spatial variation and local environmental uniqueness.

Functional unit definition and boundary selection reoccurred as the most severe in the goal and scope phase. When receiving a product system one needs to identify and prioritize functions, then define functional unit, then define reference flow. It is key to remain aware of potential errors while performing these steps. Figure 1 outlines this process.

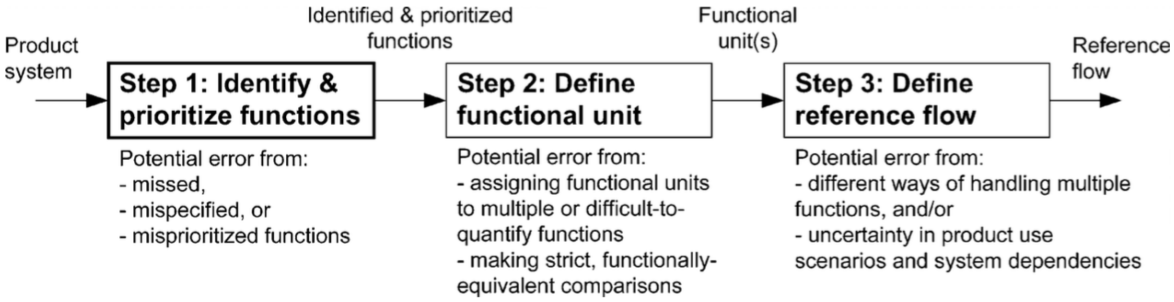


Figure 1: Potential sources of error related to the functional unit

Alternative methods to ISO exist to meet the demand for a boundary selection tool. Process-based approaches, one alternative method, have been found to exclude or cut-off capital goods. This simply is detrimental to environmental impact results (Frischknecht et al. 2007). Well-justified and transparent selection of boundaries is utilized to add credibility or confidence to the LCA results. Actively trying to increase confidence with larger boundaries may unnecessarily increase costs for the data without adding much value to the study.

Allocation is the pressing issue for inventory analysis. ISO recommends that LCA practitioners follow the stepwise procedure below (ISO 1998, 2006):

1. Avoid allocation when possible by (1) dividing the unit process into sub-processes and gathering the required environmental burden data and/or (2) expanding the product system boundaries to include additional functions related to the co-products.
2. If allocation cannot be avoided, allocate the environmental burdens of each product based on their underlying physical relationships.
3. If allocation based on physical relationships cannot be done, allocate the environmental burdens of each product based on other relationships.

(ISO)

In general it recommends that allocation procedures use the following criteria in order: physical properties like mass, economic value, or the number of subsequent uses of the recycled material.

There are uncertainty formulas, but for novice practitioners, it may be a tough task to select from the variety of uncertainty formalisms. This choice can result in a large range of results, which credits the importance of this decision. Possibility distributions, upper and lower bounds with no distributional information, fuzzy intervals, and information gaps are a few to name. The appropriateness of each one is not clear cut as to where to be used and for what uncertainty phenomenon.

To combat data inaccuracies, standardized databases of LCA data are idealized to both reduce the burdens of data collection and eliminate this uncertainty. Despite this recognition, no easily accessible, peer reviewed data sets have been created (UNEP 2003). Efforts must be directed towards both the availability of and quality of data. Data collection should include uncertainty distributions, descriptions of collection methods, sampling frequency, and dates at a minimum. As of 2006, ISO LCA standards required a company to document its data sources, which addresses many concerns about limited data that were raised by publications in the 1990's. This requirement can boost data quality if only the methods are uniform for all processes.

Overall, a standardized LCA inventory and impact databases, and development of model bases will aid the LCA industry more than any other options. Both would help alleviate persistent problems with data availability and quality. Modeling the geometry of extraction and pollution continues to prove to be an important step of research in order to include these parameters in sophisticated LCA models. There are many approaches developed towards countering these problems, which adds to the lack of agreement in the industry. Archetypes are recommended to aid in these aforementioned issues.

Conclusion

LCA is a useful and understandable approach towards environmental assessment. The flaws discussed in this piece degrade the accuracy of and increase uncertainty of results. There have been continued efforts to mitigate these problems but not one method has been agreed upon by industry professionals. The goal and scope phase deals with inclusion and exclusion decisions. Economic and social impacts are a large category that often goes excluded but this reduces comprehensiveness of a study. Concerning data quality, it is hard to know "where to draw the line between sound science and modeling assumptions" (Bare et al. 1999). Knowing this, practitioners aggregate information to expedite the process. To make decisions that affect so much using current LCA technologies is a burden for any professional. Truncation and an assumption of global homogeneity is the worse step towards solving this. With continued research and an industry trend toward normalization of methods, LCA can become a great tool going forward in product assessment.

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Appendix A: A Solar Decathlon Materials Selection Study

A Solar Decathlon Materials Selection Study

An Interactive Qualifying Project
submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfilment of the requirements for the
degree of Bachelor of Science

by

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Abstract

A team of students from the Lucerne University of Applied Sciences and Arts (HSLU) is competing at the 2014 Solar Decathlon competition in Versailles, France. Using WPI's 2013 Solatrium House as a benchmark, the purpose of this project was to observe, evaluate and document the HSLU team's material selection process for their y**our**$^+$ house. We provided recommendations to improve the entirety of the dynamic decision-making processes. In addition, we created a manual for the Life Cycle Assessment software, SimaPro®, which can be used to assist inexperienced users. The recommendations we made will help improve team strategies for future competitions.

Acknowledgements

Our team would like to thank a few key individuals for their help and support for the duration of our project. Without the guidance and continued support we would not have achieved the level of success that we had.

First, we would like to thank Professors Uwe Schulz and Shaun West, who were invaluable to our project. They were always able to provide insight to our project or help with university contacts, even with their demanding schedules outside of our project.

Second, we would like to thank the HSLU Solar Decathlon team and especially Randy Cotten for his guidance. The team was always willing to coordinate meetings and provide easy access to everything we needed on campus.

Finally, we would like to thank our advisors Professor Dominic Golding and Professor Jerome Schaufeld. The hard work and time that Professor Golding put into reviewing materials is unparalleled. Professor Schaufeld’s connections and business experience allowed us to expand our contacts throughout Switzerland.

Executive Summary

Currently, buildings account for approximately 40 percent of the total energy used worldwide and 38 percent of carbon dioxide emissions. Global warming and depletion of natural resources have increased the desire to construct more sustainable buildings. Life Cycle Assessment (LCA), also known as *ecobalance*, is a way to comprehensively track materials and energy used in any product from its creation to its disposal (i.e., cradle-to-grave assessment). There are many efforts around the globe to promote sustainable construction to reduce the amount of energy and materials in buildings, including the Solar Decathlon house competition which is sponsored by the US Department of Energy. The Solar Decathlon competition encourages universities around the world to develop more sustainable housing designs, and this year requires the use of one LCA tool, SimaPro®. The Lucerne University of Applied Sciences and Arts' (HSLU) your+ home, entered in the 2014 Solar Decathlon competition in Versailles, France, and sought our assistance to evaluate their design process and the use of SimaPro® in materials selection to promote sustainability.

The overall goal of this project was to assist HSLU in the development of systematic approaches for the selection of materials to be used in their current and future Solar Decathlon house projects. It was also to comment on the use of this type of assessment in sustainable construction. This was completed by (1) assessing the best practices in life cycle assessment in the construction industries; (2) observing, documenting, and evaluating the decision-making process of the current Solar Decathlon house team in their materials selection; and (3) developing a user-friendly and functional guide to the SimaPro® software for future Solar Decathlon House teams.

The HSLU team did a fantastic job in developing an innovative approach based on promoting sustainability through an urban design that emphasizes shared space as a way to save on materials and energy use. The approach challenges one of the fundamental emphases of the Solar Decathlon competition on the sustainability of the materials used in construction and energy generation and consumption during use. Our research focused on the team's decision making regarding materials choices. Given the HSLU team's emphasis on the design of shared space, it comes to no surprise that materials choice was given less emphasis. The conclusions and recommendations are intended as constructive criticism to enable future HSLU Solar

Decathlon teams to compete even more effectively. It is from this perspective that we wish the 2014 HSLU Solar Decathlon team good luck in the competition in Versailles, France.

Based on our assessment we made several conclusions and recommendations on team composition and decision making, material selection process, and life cycle assessment. The first conclusion is that there are numerous advantages to having an interdisciplinary team of students with diverse backgrounds and practical experience. One of the major strengths of the HSLU Solar Decathlon team was that half of the students were graduate students who had taken advanced courses that helped them with their assigned tasks for the design and construction of the prototype house. Therefore, we recommend that future Solar Decathlon teams should be recruited to include a broad mix of students with diverse interdisciplinary, theoretical, and practical skills.

Our second conclusion we made is that the Sustainability Report was an important requirement of the competition, but a major hurdle for the HSLU team due to limited English reading and writing skills within the team. We found that a major problem in the approach to the Sustainability Report (which was an important requirement of the competition) was that the main student writing it was not a native English speaker. As a result, we recommended that in the future, the student or students selected to prepare the Sustainability Report and other required documentation for the competition should be carefully selected to have appropriate skills in reading and writing English. Also, their other responsibilities for the project should be limited to ensure they can pay full attention document preparation.

Another conclusion is that the HSLU team did not establish decision making rules or procedures for resolving disputes in advance; rather their decision making process developed in a relatively ad hoc fashion. This is normal for a new team coming together to complete a large project. Every Thursday, the HSLU team came together and discussed what they completed and were still working on to inform the rest of the team. The decisions were elongated due to this. This leads to our recommendation for future HSLU Solar Decathlon team to take the time at the beginning of the process to establish clear responsibilities and ground rules for decision making and resolving disputes.

We also made conclusions and recommendations regarding the material selection process. Our team concluded that the HSLU team did not identify materials selection as a key criterion initially given their emphasis on the design of shared space as a concept. Even though the sustainability of materials was a key part of the Solar Decathlon competition, the HSLU team used other criteria initially for their selection of design, components, and materials as the Solar Decathlon competition. We recommend that any future HSLU Solar Decathlon team explicitly recognize the need to choose materials carefully based on measures of their sustainability.

The team also concluded that the scenario analysis using SimaPro® revealed that some of the materials choices made by the team were less than optimal in terms of sustainability, although these choices can be justified on various grounds. Using SimaPro®, we discovered that poured concrete would be a more sustainable option over wood and steel for the foundation of the y**our**$^+$ house and that urea formaldehyde foam and cellulose fiber were better options in terms of environmental impact than the rock wool. We recommend that the current HSLU team use the data from our analysis and SimaPro® to explain to the Solar Decathlon judges that they recognize the limitations of their materials selection for the prototype. We also recommend that the HSLU team explain to the Solar Decathlon judges that additional materials analysis using SimaPro® and/or other LCA tools will be used to identify more sustainable materials for use in the full-scale concept building for which the y**our**$^+$ house is a precursor. Lastly, we recommend that future HSLU teams use SimaPro® or other LCA tools to help choose and justify materials selection choices.

The HSLU team's decision making process for materials selection was ad hoc, and their organization of the master list was less than optimal due to the belated focus on materials selection. The team also utilized the contractor Renggli late in the Construction Phase. The HSLU team did incomplete research into the sustainability of potential materials and did not log data into a single Microsoft Excel™ sheet for the master materials list. As a result, there were many versions of the document with different material information on each version. Additionally, students on the HSLU team recognized working with the contractor earlier in the Design Phase would result in a more efficient Construction Phase because the contractor could review the building designs sooner and provide their expert opinion.

We recommend the next HSLU Solar Decathlon team adopt the Material Selection Process that we proposed. It is divided into three phases: Design, Construction, and Review. In the Design Phase, the HSLU team should take into consideration researching common materials versus sustainable materials by using material selection software. In the Construction Phase of our recommended process, the contractor should order materials to begin the construction of the house. Finally, the Review Phase consists of completing construction on the house and conducting a post-analysis with SimaPro®.

Lastly, the team made conclusions regarding Life Cycle Assessment (LCA). The first conclusion we made was that SimaPro® has a steep learning curve and takes considerable time and effort to master. The complexity of the software did not allow the HSLU team to benefit from the in depth comparisons and analysis that can be produced. This lead to two recommendations: future HSLU teams should use the SimaPro® Guide we developed and designate one person per disciplinary group to learn SimaPro®. Also, SimaPro® needs to simplify its user interface and improve its support network.

SimaPro® provides enormous analytical power which may not be necessary or desirable for initial materials selection, but can be extremely useful for checking, justifying, and demonstrating decisions after the fact. Our group concluded, with the given guidelines from the Solar Decathlon competition, that SimaPro® is best used as a justification tool. Therefore, we recommend that future HSLU teams use simpler LCA tools, such as Bauteil Katalog, or hand calculations to assess material sustainability. SimaPro can be used to provide more in-depth analysis of selected materials decisions to justify choices made.

Another conclusion is when constructing a sustainable building, life cycle assessment methods in conjunction with the ecoinvent database is the best practice. In spite of the accuracy of SimaPro®'s ecoinvent database, it is not utilized by industries to its fullest potential in all countries. We recommend that rising architects and engineers familiarize themselves with the practices of LCA and databases like ecoinvent. The construction industry should also head towards using software programs that incorporate ecoinvent, like SimaPro®. If future HSLU Solar Decathlon teams consider our recommendations, we believe it would support their success in the Solar Decathlon competition.

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2.2 Overview of Material Life Cycle	Timothy Love	All
2.3 Introduction to LCA	Timothy Love and Lauren Tice	All
2.4 Rating Systems, Standards, and Guidelines	William Michalski	All
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2.6 Limitations of LCA	Lauren Tice	All
2.7 HSLU's Interest in Solar Decathlon and LCA	Lauren Tice	All
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3.1 Objective 1: An Assessment of Best Practices in LCA	All	All
3.2 Objective 2: Material Selection	All	All
3.3 Objective 3: A Guide to SimaPro®	Timothy Love	All
3.4 Conclusion	All	All
Chapter 4: Findings	All	All
4.1 Team Selection, Composition, and Decision Making	All	All
4.2 HSLU's Performed Material Selection Process	All	All
4.3 Existing LCA Tools	All	All
Chapter 5: Conclusions and Recommendations	All	All
5.1 Team Composition and Decision Making	Lauren Tice	All
5.2 Conclusions Regarding the Material Selection Process	Azarmeedokht Azizi	All
5.3 Conclusions Regarding Life Cycle Assessment	Timothy Love and William Michalski	All

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1. Introduction

Academics, environmentalists, and many policy makers have become increasingly concerned that increasing consumption of energy threatens to deplete global resources and results in a variety of adverse environmental impacts including climate change. Beginning in the 1960s, academics and practitioners developed Life Cycle Assessment (LCA). LCA, also known as ecobalance, is a way to comprehensively track materials and energy used in any product from its creation to its disposal (i.e., cradle-to-grave assessment). The tools and approaches to LCA have evolved over the following years and have been applied to a variety of modules and projects. Increasingly, these tools are being used in the construction industry as it grapples with how to make buildings more sustainable. To overcome this issue, there are many efforts around the globe to promote sustainable construction to reduce the amount of energy and materials in buildings, one of them being a competition between universities.

The Solar Decathlon, started in 2002 by the United States Department of Energy, is a biannual competition that challenges students from different universities around the world to design the most "cost effective, energy-efficient, and attractive house" that is powered by solar energy ("Solar Decathlon", 2014). The solar house must be affordable, supply energy for household appliances, provide hot water, and produce a greater or equal amount of energy than it consumes. Using a life cycle assessment tool called SimaPro®, materials are analyzed to ensure that each team's solar house promotes environmental sustainability. Over twenty teams were registered to compete in the 2014 Solar Decathlon, which will be held in Versailles, France. One of these teams is the Lucerne University of Applied Sciences and Arts (HSLU) and its y**our**$^+$ house design.

The vision for the y**our**$^+$ house was to create a sustainable home that utilizes less living space for each person. Switzerland is running out of space for residential land due to both population increase and the demand for more living space per person. The average person needs fifteen more cubic meters of living space now than they did 100 years ago. The y**our**$^+$ home utilizes shared space between tenants in the larger concept building as a series of modules. Each module will have a *my room*, *your room*, and *our room*, and are connected by an area defined by HSLU as **space**$^+$. *My room*, which contains the bedroom and bathroom, is meant for single inhabitants or couples. This is the portion of the module that is the most private and intimate. *Our room* is the kitchen and entertaining area, meant to be used for all inhabitants of each individual module. *Your room* is a common space shared between everyone in the module that may be used in a variety of ways.

A goal of our project was to assist HSLU in the development of systematic approaches for the selection of materials to be used in their Solar Decathlon house projects. At the time of our arrival in Switzerland, HSLU was in the process of completing its solar house design and were hoping for our help in the areas of decision making and material selection. Our team documented the decathlon team's decision-making process as they chose materials for their y**our**$^{+}$ concept house. We conducted interviews and focus groups with students to understand their material selection process.

HSLU was interested in LCA because it had the potential to help them choose appropriate materials to maximize sustainability. A rounded knowledge of LCA helped us make recommendations on the process that the team can use in the future. LCA tools such as SimaPro® were intended to be used to help make these recommendations. SimaPro® was a great post-selection analysis tool which we used to compare materials. The life cycle of a product can be viewed as cradle- to-grave analysis. The product is obtained (harvested, mined, synthesized, processed, etc.), transported, manufactured, packaged, maintained, and finally disposed. This life cycle assessment is where SimaPro® is used to compare materials. It was our goal to help the HSLU Solar Decathlon team document their decision-making techniques, provide them with a streamlined approach to future material selection, and create a users' guide to SimaPro®.

2. Literature Review

2.1 History of LCA

The idea of Life Cycle Analysis (LCA) began in the 1960's as academics and practitioners became increasingly concerned about the adverse impacts of the growing use of energy and other resources. Public and academic concerns about the impact of population and economic growth on finite resources and levels of pollution were heightened by the publication of landmark studies such as *The Population Bomb* (Ehrlich and Ehrlich 1968) and *The Limits to Growth* (Meadows *et al.* 1972) These studies were severely criticized on ideological and methodological grounds but they stimulated an enormous effort to develop better methods to assess the environmental impacts of economic growth and the exploitation of energy and other resources. Concern about material consumption and depleting resources boosted the development of LCA. While the early studies focused on the risks of resource depletion in particular, the concern has shifted more recently to global climate change as a result of fossil fuel consumption.

The study that set the foundation for LCA in the U.S. was a study for the Coca-Cola Company in 1969 that was carried out by Harry E. Teasely. The study was never published because it contained confidential information (Hunt, Franklin, & Hunt, 1996). Researchers determined which drink container used the least natural resources and had "the lowest releases to the environment" (Curran, 2006). The study collected information on what materials and fuels were used starting with the manufacturing of the container. In the early 1970's, other companies began conducting similar studies on their products.

In the U.S., Resource and Environmental Profile Analysis (REPA) became the process of analyzing resources used in various products in terms of energy and tracking potential impacts in the environment. In Europe, this process was called ecobalance (Curran, 2006). It was not until 1990 that the term LCA came into general use in the U.S. (Hunt et al., 1996).

Although ecobalance and LCA may be used interchangeably, there is a difference between them. Ecobalance is a mindset and an area of sustainability that utilizes LCA. After a LCA is performed on a product or a building, it is ecobalanced or completed with ecobalance in mind. Another way to distinguish between them is that LCA is the method used to evaluate a product or building and ecobalance is what is done with the data to apply it and make it useful.

Between 1970 and 1975, before LCA came into general use, many REPAs were completed mostly because of concerns about the shortages of oil. However, when the oil crisis faded, concerns shifted to “household waste management” (Curran, 2006). In the early 1970’s, solid waste was recognized as a global problem and drove LCA to surface as a way to analyze the attendant environmental problems (Hunt et al., 1996). Some LCAs only focus on energy, some only on materials, and others focus on both. Sometimes LCA does not focus on the whole process of a product, rather it focuses on one aspect of the life cycle such as use, disposal or manufacturing. Over the years, concerns have surfaced over product manufacturers inappropriately using LCAs to make marketing claims. This concern along with pressure from environmental organizations to standardize LCA procedures, led to the creation of LCA standards in the International Standards Organization (Curran, 2006).

2.2 Overview of Material Life Cycle

In the simplest terms, the life cycle of a product begins with the extraction of raw materials and ends with its disposal, typically in a landfill or incinerator (Figure 1). Life stages of materials are inter-dependent and are constantly influencing one another. Each phase in the life of a product has direct and indirect impacts on the environment. Life cycle assessment tries to identify and estimate the impacts at each of these phases to derive an estimate of the total impact of a particular product.

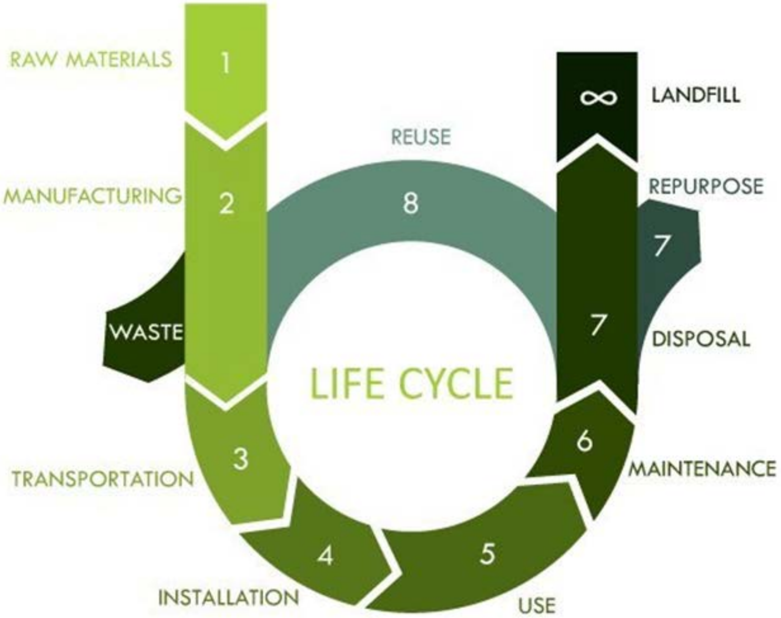


Figure 1. Product Life Cycle (Clemson, 2012).

Figure 1 illustrates the typical phases in the life of a product. First the raw materials are extracted through a range of processes from harvesting crops or cutting down trees for timber to removing metals and other elements from the Earth. Step two entails manufacturing the product. This step is elongated in Figure 1 to indicate that manufacturing typically entails the use of more energy than do the other steps in the life cycle of the product. The subsidiary arrow labeled ‘waste’ refers to the waste generated during the manufacturing process. This is important for LCA because minimizing waste generation is a key aspect to establishing environmental sustainability. Transportation can be by any sort or vehicle (truck, ship, and airplane) and refers to transport at any point in the life cycle of the product from shipping raw materials to final disposal. Installation accounts for the labor, energy and outside resources that are required to make the product operational. Step 5 (product use) can be one of the longest or shortest depending on the product’s nature and purpose. During the use part of the life cycle many products and systems and will need maintenance. Maintenance will allow the product to properly function at optimal capacity without harming the environment and reducing its carbon footprint. At some point, all products reach the end of their useful life. Products may be repurposed or reused in various ways, or they may be disposed of in a landfill or incinerator. If the product is reused it will go through the cycle again, as shown in Figure 1.

2.3 Introduction to Life Cycle Assessment

LCA consists of several components (Figure 2). The first is goal definition and scoping which is when the product or process is defined, the boundaries of analysis are set, and the type and range of environmental effects are identified. The next step is to conduct a life cycle inventory analysis (LCI) to quantify the water, energy, and material usage along with releases into the environment. The third step is to complete a life cycle impact assessment (LCIA). The data on water, energy, and material use in the inventory analysis are used to assess the potential environmental effects. The final step is interpretation of the inventory analysis and impact assessment to choose the preferred product or process. LCA is an enormously complex process and the quality of the assessments is based on the nature of the uncertainties associated with key variables and the types of assumptions that must be made in order to conduct the analysis (Curran, 2006).

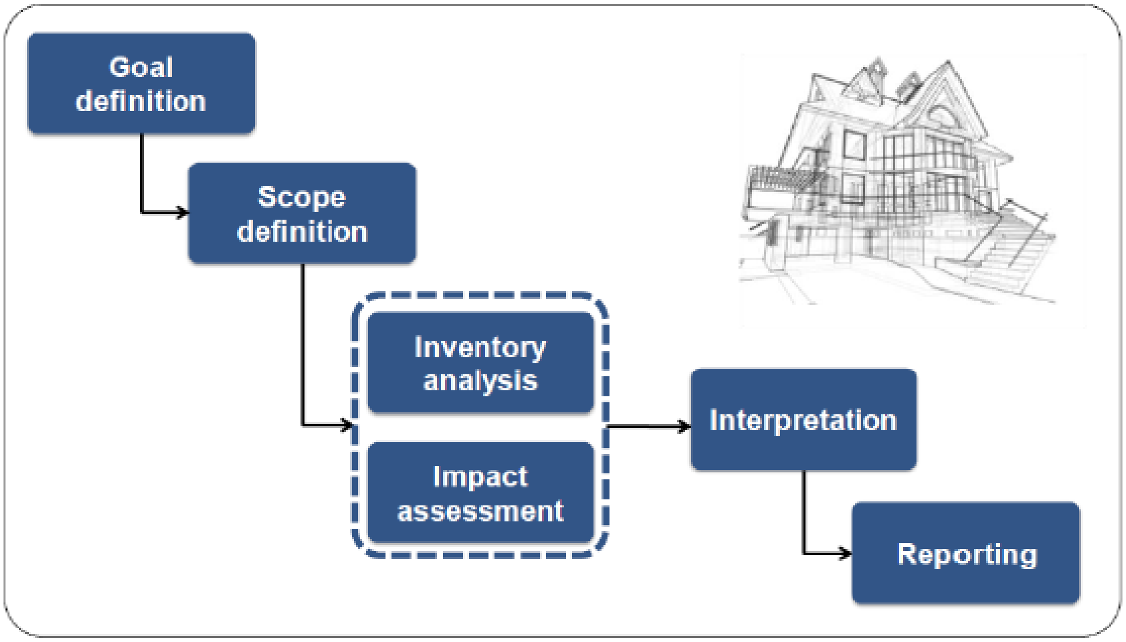


Figure 2. Steps of LCA ("Thermal and Environmental Evaluation Information Guide V2", 2013).

Every day the world gets more conscious of the choices and actions people make affect the environment. This puts a social as well as an economic pressure on the construction industry, they need to conform to what the consumers and investors need. Increasingly the construction industries in the U.S., Europe, and elsewhere in the world are using LCA, to optimize the use of sustainable and environmentally friendly materials and processes. LCA allows for the comprehensive selection of building materials that will reduce regional, national and global environmental impacts, such as ozone depletion, eutrophication, and acidification. LCAs are often applied as decision support tools for selection between different alternatives providing the same product or service. A LCA is quantified by the concept of a “functional unit” that defines the product or service (Turconi, 2013). The functional unit defines what precisely is being studied and quantifies the efficiency of the service being delivered. This functional unit provides a baseline in which all inputs and outputs of a given system can be related. Once the functional unit is found then the process for the optimal alternative can be used and evaluated over many scenarios.

Castells examined recent developments in LCA the construction sector. He distinguishes between approaches that focus on “building material and component combinations (BMCC)” and those that assess the “whole process of the construction (WPC).” Castells talks about how BMCC, used in 2009, focuses on eco-design. Eco-design is the relationship between a product and the environment during the design of products, processes, activities and dematerialization (Castells, F., 2009). Applying eco-design and LCA together will produce a procedure to pinpoint a product or products that have been evaluated through each stage of the life cycle to reduce environmental harm.

Castells examined 25 case studies conducted in the United States during the early 2000’s. Most focused on embodied energy of industry-produced building materials like concrete, ceramic, glass and steel. Based on these assessments of the whole construction process, he concluded that buildings are the largest consumers of energy in the U.S. and the largest sources of greenhouse gases (Castells 2009). In the U.S, “residential and commercial buildings … consume about 40% of the country’s primary energy and emit 20% of the national carbon dioxide budget” (Intelligent Sustainable Design, 2011).

One case study that Castells referenced was a study of a three bedroom semi-detached house in Scotland. The main materials of construction were wood, aluminum, glass, concrete and ceramic tiles and they were evaluated to determine their ‘embodied energies’ as well as their environmental impacts. The term embodied energy is the total amount of energy used to produce a product.

Although the techniques of LCA have been used for more than 30 years, they have only been applied recently in the construction industry. Cabeza (2014,1) defines LCA as “comprehensive, systemic approach to environmental evaluation, interest is increasing in incorporating LCA methods into building construction decision making for selection of environmentally preferable products, as well as for evaluation and optimization of construction processes”. While Castells differentiates among three types of LCAs based on construction sector, Cabeza (2014, 1) distinguishes between life cycle energy analysis (LCEA) and life cycle cost analysis (LCCA). Life cycle cost analysis is an economic evaluation technique that determines the total cost of owning and operating a facility over a period of time. By contrast, life cycle energy analysis is an approach that accounts for all energy inputs to a building during its life from construction to demolition. Table 1 below breaks down the components of LCA according to Cabeza (2014) including the name of the concept, its acronym, and a brief conceptual definition.

Table 1. Life Cycle Assessment Acronyms (Cabeza, 2014, 2.1).

Acronym	**Concept**	**Definition**
LCA	Life cycle assessment	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle
LCI	Life cycle inventory analysis	Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle
LCIA	Life cycle impact assessment	Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product
–	Life cycle interpretation	Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations
ILCD	International reference life cycle data system	ILCD consists of the ILCD Handbook and the ILCD Data Network. It provides governments and businesses with a basis for assuring quality and consistency of life cycle data, methods and assessments

Cabeza points out that in order to optimize energy, cost, and sustainability a more comprehensive assessment needs to include the construction, use and disposal of non-recycled parts (Cabeza, 2014). Companies and construction firms are less likely to use an environmentally friendly option when the option is at a much greater cost. This includes money as well as time. This process of reviewing the life cycle factors from “owning, operating, maintaining, and disposing of a building or a building system” all factors into the total cost. Total cost is calculated over a specific period that the building is expected to be operational. When improvements and upgrades to the build occur, the LCC is reevaluated to form to the new constraints.

In contrast with LCCA, LCEA focuses on all energy inputs to a building in its entire life cycle from construction through use and demolition. Energy input can come from a variety of sources. The manufacturing process encompasses the energy used to acquire the raw materials, transport to the manufacturing site, power input needed to make the material, transport to the site, and the renovation/maintenance (Cabeza, L. F., 2014).

2.4 Rating Systems, Standards, and Guidelines

The construction industry is gradually moving towards more sustainable construction techniques and materials. Many countries are putting regulations in place that require the use of more sustainable construction. Different countries have adopted different kinds of approaches but many are moving in the same direction. Discussed below are a number of these approaches that have individually, but successfully encouraged more sustainable techniques and materials.

2.4.1 Construction Specifications Institute (CSI)

A common categorization of construction materials was developed by the Construction Specifications Institute (CSI) in the U.S. It contains 25 divisions; one of them includes specifications for everything from electrical devices to window openings to masonry. Typically, the architect stipulates the specifications, but owners, contractors/ subcontractors and product manufacturers all have authority to select materials. Each party may have a different level of influence depending on the phase of the project. The common phases of a project are: Schematic Design, Design Development, Construction Documents, Bid and Award, then Construction Administration. “Rating systems, standards, and guidelines can be classified into two groups: those that relate to specific building components and those that relate to the building as a whole entity” (Green Building, 2011). Different organizations have tried to develop strategies based upon the distinction of individual parts installed within a building or the overall environmental functionality of the building.

2.4.2 The International Organization of Standardization and the British Standard Institute

There are several standards for the conduct of Life Cycle Assessment (LCA). The International Organization of Standardization (ISO) created ISO 14040:2006 which provides a description of the procedure for LCA. It contains information on the four stages of LCA: the definition and scope of LCA, the LCI, LCIA, and the interpretation phase. It also discusses the limitations of and the relationship between the LCA phases. It does not however prescribe in detail the procedures for each of the four phases of LCA. Instead, the standard emphasizes the need for clear and consistent assumptions to allow comparison between the results of LCA and LCI studies. The standard provides recommendations on how to analyze those results (Standardization, 2006a). Another standard (ISO 14044:2006) specifies the four stages of LCA but gives more detail on the methods for conducting LCA and LCI studies (Standardization, 2006b). The British Standard Institute (BSI) developed PAS 2050, a standard that contains carbon footprint measurement tools. This standard addresses the need for a procedure and standardization in analyzing greenhouse gas admissions in the life cycle of products ("Greenhouse Gases; carboNZero Holdings Becomes the First Non-UK Company to Provide PAS 2050 Certification," 2012).

2.4.3 United States Green Building Council

Experience and technological advancements have refined LCA, also hastening the adoption of sustainable practices. The detail of standards, quantity of data, and influence of organizations tend to be greater in the places which have the greatest experience. The United States Green Building Council (USGBC) is an organization founded in 1993 that incentivizes the practice of green building. USGBC's mission is "to transform the way buildings and communities are designed, built, and operated, enabling an environmentally and socially responsible, healthy, and prosperous environment that improves the quality of life" (Green building, 2009). The USGBC refers to the progression following the environmental revolution of the late 20th century, "This transformation will never be complete, since green building is fundamentally a process of continual improvement. In this process, today's 'best practices' become tomorrow's standard practices and the foundation for ever-higher levels of performance" (Green building, 2009). Part of these standard practices can be found within the rating system: Leadership in Energy and Environmental Design (LEED) developed by the USGBC.

LEED certification has gained increasing popularity in North America and in the United States the U.S. General Services Administration requires that all new federal government construction projects and substantial renovations achieve LEED certification. In order to accomplish their mission, USGBC have created goals as an organization to "accelerate the adoption of green building practices, technologies, policies, and standards" (USGBC, 2006). LEED and a number of other tools have been developed to ensure buildings meet these requirements.

2.4.4 Leadership in Energy and Environmental Design

"In 2007, the Green Building Certification Institute (GBCI) was established as a separately incorporated entity with the support of the U.S. Green Building Council" (Green building, 2009). The GBCI is in charge of the LEED Professional Accreditation program independent of USGBC. The GBCI's services are exam development, registration, and delivery. Three stages of certification are: LEED Green Associate, LEED Accredited Professional (AP), and LEED Fellow. To be a LEED AP, GBCI provides continued education to maintain current practices. LEED is often compared to Energy Star, a joint program of the US Environmental Protection Agency (USEPA) and the US Department of Energy (USDoE). The EPA introduced this campaign in 1992 on a voluntary basis to reduce green-house gas emissions, but it has developed into rating energy use of household appliances to industrial and commercial equipment (Cole, 2006). Energy Star is generally limited to energy efficiency and is a single attribute system. LEED, contrarily considers many green attributes, making it multiple attribute rating system. In addition to this, LEED's guidelines refer to other environmental standards instead of setting new criteria, making them easier to implement.

With the aid of its partner, GBCI, the USGBC uses LEED to incentivize the construction industry. LEED is a third-party organization that helps with USGBC ambitions for the U.S. to push towards greener designs. However instead of implementing sustainability, it inspires businesses to follow the green design. As of 2011, many states have some sort of legislation on green building: orders, bills, laws, including 18 states that required all publically owned buildings achieve LEED Silver (Green building, 2011). As of 2011, there were over 1,900 LEED certified projects in the U.S., with over 15,000 registered for certification. LEED, however, is not an end in itself, but a means that provides tools as framework for design, construction, and evaluation.

For example, college campuses are popular sites to implement sustainable structures. Colleges wish to demonstrate that they are on the 'leading edge' in promoting sustainability and can accommodate the higher capital costs since they recognize the long-term benefits of building to LEED specifications. LEED can also establish programs where they can teach university leaders how their system works (Chance, 2012). Although there are registration fees, "the USGBC has asserted that a LEED-certified or Silver-rated building should not cost more than a conventional building. (Gold or Platinum rated buildings may cost more…" (Green building, 2011). As of 2011, the USGBC charges a fee of at least $900 for registration, $2,000 for design review, and $500 for construction review. The fee for larger buildings is as high as $0.45/SF (Green building 2011). Once a project team is finished their project and goals need to be realized or not, measurement is critical. If a goal of a project team is to minimize life cycle cost through sustainable design principles then it is vague as to whether this goal is reached. Energy performance goals may be set such as the annual energy cost per gross square foot (BTU/SF/year).

2.4.5 LEED Rating Systems

Traditional LEED could be referred to as LEED-NC representing New Construction. A table outlining the potential for points can be found in Appendix D. LEED has six focus areas for their credit system: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, and Innovation and Design Process. There is sometimes a seventh category that has been developed by chapters, Regional Priority (Green building, 2009). This criterion, added in 2009, addresses regionally important issues.

Through opportunity for growth from popularity, the USGBC has launched numerous programs. LEED rating systems cover new construction, ongoing operation and maintenance, as well as major tenant retrofits. “LEED rating systems address the following types and scopes of projects:

- LEED for New Construction
- LEED for Core and Shell
- LEED for Commercial Interiors
- LEED for Schools
- LEED for Healthcare
- LEED for Retail
- LEED for Existing Buildings Operations and Maintenance
- LEED for Homes
- LEED for Neighborhood Development” (*Green building*, 2009)

Most of these rating systems have 110 total potential points with varying levels of compliance (Certified: 40-49, Silver: 50-59, Gold: 60-79, Platinum: 80+) (Green building, 2009). To be LEED certified, a project must satisfy all prerequisites and earn a minimum number of points. Points are awarded for additional features that make the project sustainable. Greatest weight of points is given to credits that most directly influence the important environmental areas of human benefit. Quick ways to understand sustainable construction practices can be found in Appendix

E which contains listed general areas of a building that can be drastically improved upon sustainably.

Design and sustainability is based upon a ‘triple line’ approach. In 1994, John Elkington coined this phrase “…to refocus the measurement of corporate performance from the perspective of a shareholder (predominantly financially driven) to that of a stakeholder (anyone affected by the actions of a firm) and coordinate three interests: ‘people, planet, and profit’” (*Green building*, 2009). The USGBC adapted his approach and since has developed “metrics and rating systems” to distinguish LEED buildings from others. The three dimensions of sustainability in the triple line theory as displayed in Figure 3 are society, the environment, and the economy.

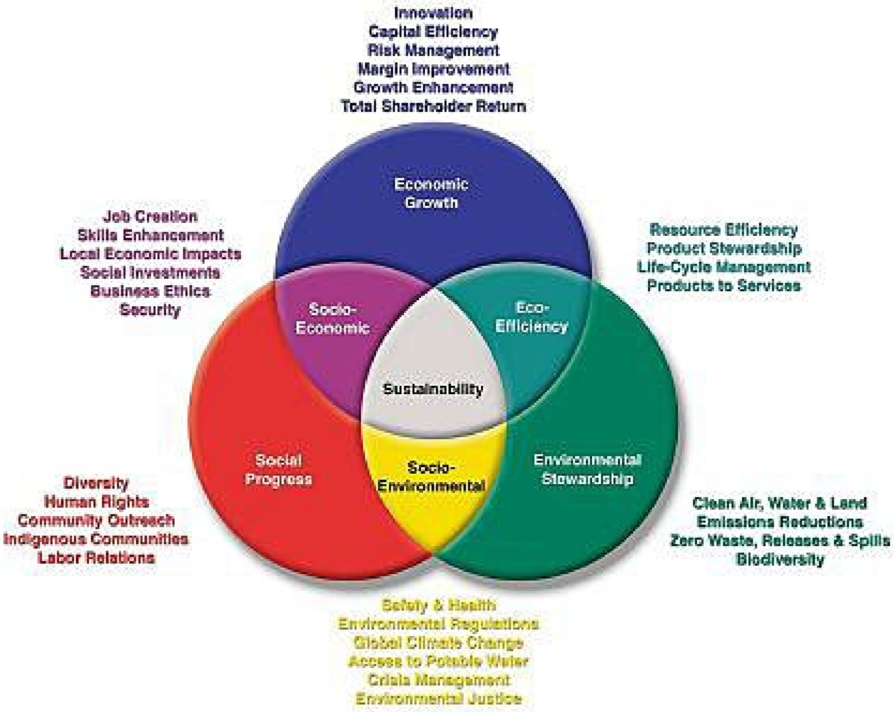


Figure 3. Triple Bottom Line (Gaia University, 2010).

This three dimensional system is often compared to a three-legged stool where if the legs are not equal the stool will wobble and render it not functional. To be LEED certified demonstrates that the project has addressed and balanced each of the three areas of the triple bottom line which are the three dimensions of sustainability.

2.4.6 Minergie®

Minergie® is the Swiss green building standard that is equivalent to LEED and was launched in 1998. Minergie® is a private, non-profit organization that is supported by the cantons of Switzerland, schools, companies, the federal government, and other associations (Salvi & Syz, 2011). There are three levels of Minergie® building certifications. The first is the basic Minergie® certification which is used for new and renovated buildings. In order to receive this certification, the building must have a reduction of energy consumption of at least 25% as compared to average buildings. To determine whether or not a building meets the requirements of the basic Minergie® certification, energy consumption is estimated based on the materials used (Salvi & Syz, 2011). Also, the fossil-fuel consumption must be less than half of existing average conventional buildings. A stricter level of Minergie® certification is called Minergie-P®. It calls for a very low energy consumption and contains high demands for heating energy (Salvi & Syz, 2011). The third level of Minergie® building certification is Minergie-ECO® which "verifies the use of environmental-friendly building materials" (Salvi & Syz, 2011) and adds "ecological requirements such as recyclability, indoor air quality, noise protection etc. to the regular Minergie® requirements" (Schoch, 2010b).

Minergie® has been very successful since it first began. Between 2004 and 2009, the number of new Minergie® buildings tripled. Figure 4 shows a breakdown of the number of Minergie®-certified buildings for each type of building since 1998.

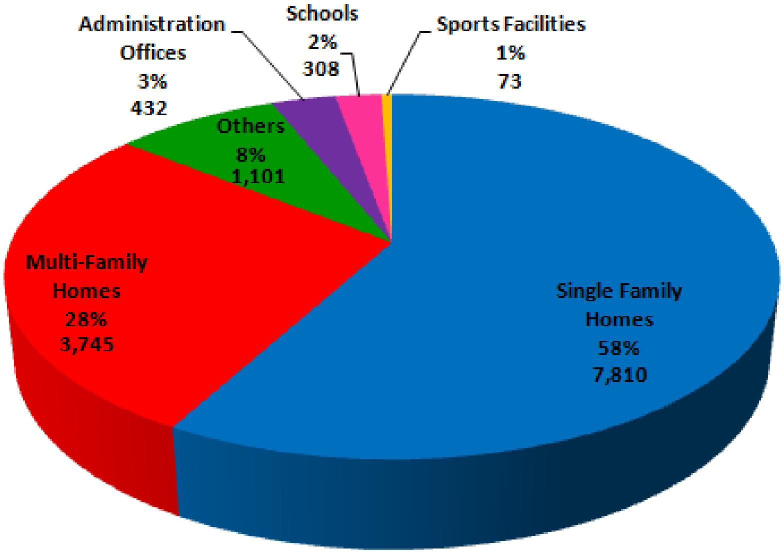


Figure 4. Number and Type of Minergie-Certified Buildings since 1998 (Salvi & Syz, 2011).

Even though about one percent of the existing buildings in Switzerland have been Minergie® certified currently, "Minergie's penetration rate in Switzerland is roughly 280 times higher than LEED's rate in the United States" (Salvi & Syz, 2011). Some areas in Switzerland have a larger number of new Minergie® certified residential buildings than others (Figure 5). Table 2 shows the number and proportion of new buildings that are Minergie®-certified by major city in Switzerland. Geneva has the highest proportion of Minergie®-certified buildings but this reflects the relatively small number of new buildings built in Geneva between 2004 and 2008. Zurich has the highest total number of Minergie®-certified buildings among all Swiss cities.

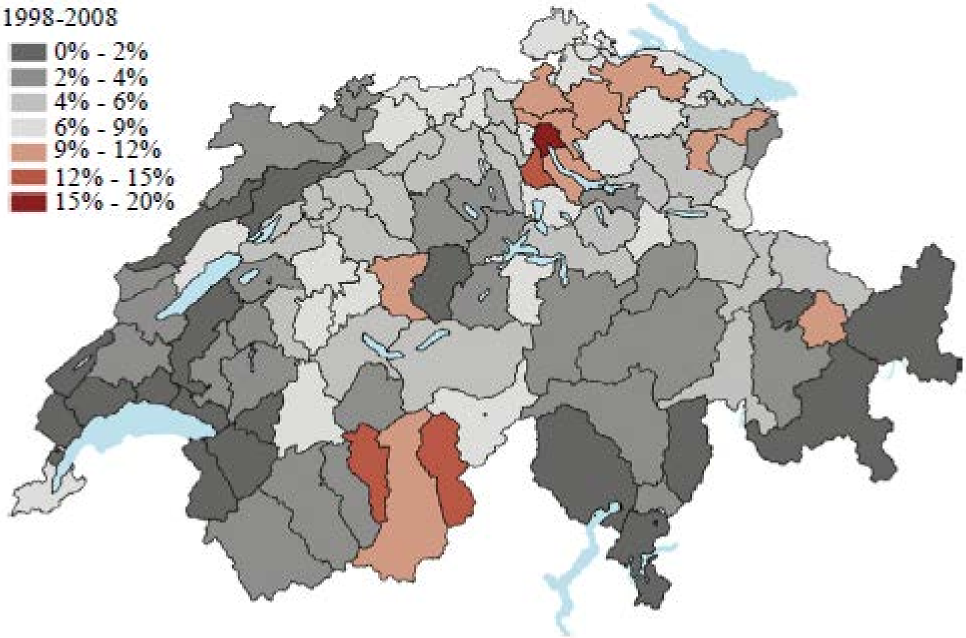
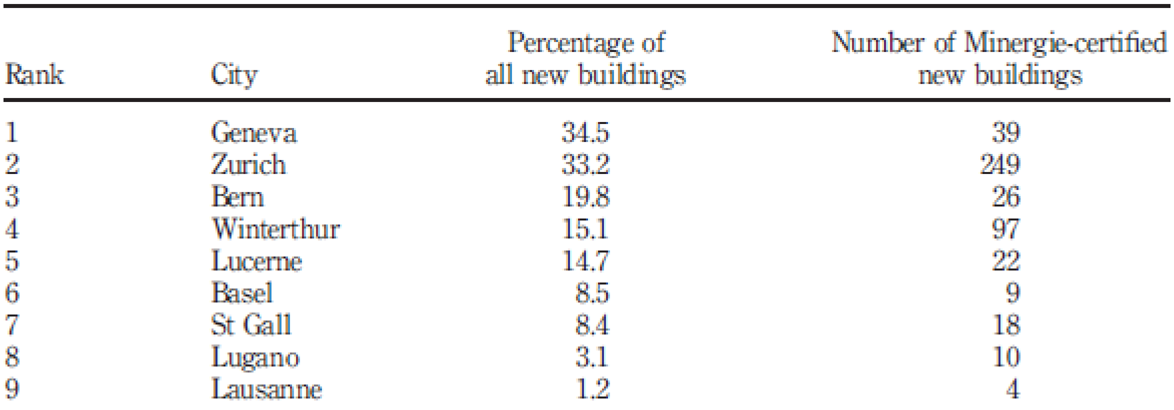


Figure 5. New Minergie® Residential Buildings by Region in 1998-2008 (Salvi & Syz, 2011).

Table 2. Construction Activity in Switzerland's Major Cities in 2004-2008 (Salvi & Syz, 2011).



Rank	City	Percentage of all new buildings	Number of Minergie-certified new buildings
1	Geneva	34.5	39
2	Zurich	33.2	249
3	Bern	19.8	26
4	Winterthur	15.1	97
5	Lucerne	14.7	22
6	Basel	8.5	9
7	St Gall	8.4	18
8	Lugano	3.1	10
9	Lausanne	1.2	4

Although Minergie®-certified buildings cost two to ten percent more than non Minergie®-certified buildings, there is a reward scheme that entices Swiss developers to build Minergie®-certified buildings. Large banks perceive mortgages for Minergie® constructions to be very reliable and as result give Minergie® builders a better interest rate. In addition, a study by Zurich University found that "buyers are willing to pay seven percent more for family houses with a Minergie® certificate" (Schoch, 2010a). The main reason is the better interest rate, but also Minergie®-certified buildings increase in value over time. Due to the reduction in energy consumption, the additional costs of a Minergie®-certified building are typically recouped after about seven years (Schoch, 2010a).

2.5 Tools

Today, buildings use large amounts of energy primarily for heating and cooling, although much energy is also embedded in the materials used. The Department of Energy estimates that buildings use 40% of all energy consumed in the U.S. and U.S. buildings are responsible for 8% of global greenhouse gas emissions (DOE, 2010). LCA tools can play an important role in reducing these emissions if they can help architects, engineers, and the rest of the construction industry build more energy-efficient buildings with less energy intensive materials. Assessments of energy efficient buildings can aid in the selection process of materials. When using LCA to design a building, the initial total cost could be high, but the cost of maintenance over time will be lower than a building that does not use LCA. Some examples of energy analysis tools include

The Building for Environmental and Economic Sustainability (BEES®), ATHENA® EcoCalculator, ATHENA® Impact Estimator, Sustainable Minds, GaBi, SimaPro®, and Bauteil Katalog.

2.5.1 The Building for Environmental and Economic Sustainability

The Building for Environmental and Economic Sustainability, also known as BEES®, is a tool created in the United States to select materials that are best suited for a sustainable building design. From gathering raw materials to installation, BEES® can measure economic performance and environmental impact no matter which step in the building process the user is in. There are three steps that the user must follow in order to take advantage of the BEES® software: set the parameters, select alternative building products, and view the BEES® online results. Setting the parameters allows users to "choose environmental impact category weights from three pre-defined weight-setting categories or define weights by selecting the user-defined weight set" (Han, 2011). There are many materials the user can choose from as there are "two-hundred and thirty products" which are then "divided into seven major group elements" (Han, 2011). The product is also given a score, which determines its overall performance.

2.5.2 ATHENA® EcoCalculator

ATHENA® EcoCalculator was created by the Athena Institute along with the University of Minnesota and Morrison Hershfield Consulting Engineers. This program helps relate and contrast different building based on their sustainability. It considers "global warming potential, acidification potential, ozone depletion potential, HH respiratory effects potential, eutrophication potential, and smog potential" (Han, 2011). Although this calculator determines the environmental impact of building materials; however, "it does not estimate or account for operational energy" nor the associated economic costs of these analyzed materials (Han, 2011).

2.5.3 ATHENA® Impact Estimator

ATHENA® Impact Estimator (IE), "is the only software that is particularly designed to evaluate whole buildings based on life-cycle assessment methodology" (Han, 2011). Although IE cannot analyze section of the building or even specific materials, it is "capable of modeling well over 1,000 structural and envelope assembly combinations" (Han, 2011).

2.5.4 Sustainable Minds

Sustainable Minds is more recent web-based LCA tool that does not require a download. Users specify what "elements each product should be evaluated and compared by" and how long the product should last (Hicks, 2010). Material selection, production methods, and transportation information are input next. A major advantage of Sustainable Minds is that users can upload a list of materials from 3D modeling programs which means material information does not have to be manually entered. Once all the information is entered, charts are generated that informs the user which phase of the product's life cycle impacts the environment the most. The program also allows side by side comparison of these charts to compare different material information. Sustainable Minds has a section of their website "dedicated to helping designers understand eco-design strategies that may help reduce the impacts" (Hicks, 2010).

Despite the ease of use of Sustainable Minds, there are limitations to the program. One of the main limitations is that "impact methodology is limited to one approach, in which all the environmental impacts are rolled into a single number, or single-indicator" (Hicks, 2010). This greatly simplifies the results but makes the program better suited for beginners or students to use.

2.5.5 GaBi

GaBi is a LCA tool which helps with "process(ing) optimization, cost control, environmental criteria, and external representation of results" (Wilkinson, 2012). Some disadvantages to using this tool are that it takes time to learn how to use it, due to its intricacy. However, it is still used due to its "intuitive user interface and structure", which allows for "flexible inputs and outputs", and includes many materials, not necessarily "limited to plastics, organic and inorganic products" (Wilkinson, 2012). GaBi requires users to create a "process-tree" which connects energy, processes, and materials to parts. Users can display the inputs and outputs and see how they would impact the environment (Hicks, 2010). Users have the option of selecting from various impact methodologies such as global warming potential, eutrophication potential, and acidification potential.

A major advantage to this program is that it can be complex to use but there are many tutorials and guides available to aid users. Compared to its competitors, GaBi is fairly intuitive to use. In addition, GaBi "utilize[s] data sets made up of industry averages for thousands of processes; industry-specific and custom data sets are also available" (Hicks, 2010). Its disadvantage is that it is complex and is unable to support multiple users (Wilkinson, 2010).

2.5.6 Bauteil Katalog

Bauteil Katalog is a Swiss based tool available online which allows for visual display of environmental impact. It has a default setting with preset construction material and the scope of the work can be set to any section of the life cycle assessment. It measures several impacts of the building materials, such as embodied energy, primary energy, global warming, and ecological scarcity. Bauteil Katalog produces results with a 10% variation and can do side-by-side comparisons of different materials. It uses ecoinvent to analyze building materials and whole building analysis.

2.5.7 SimaPro®

SimaPro®, a tool developed by Pré Sustainability used to analyze individual materials, "comes with a large set of data libraries (and) covers all the details of life-cycle analyses" (Han, 2011). Similar to GaBi, SimaPro® is generally used by LCA professionals. There are many applications SimaPro® can be used for such as: "carbon footprint calculation, product design and eco-design, environmental product declarations", and many more ("Thermal and Environmental Evaluation Information Guide V2," 2013). SimaPro® also allows users to map the material's life cycle including its transportation and disposal. Various fields of engineers can use this to analyze their projects. A downside to this program is that "it takes…a more significant time investment" to be able to understand it and use it proficiently (Han, 2011). The program can also get very detailed depending on what task you give the program to analyze. However, an advantage is that it has the ability to compare two or more products (Wilkinson, 2010).

Ecoinvent, a database within SimaPro®, has a goal to combine life cycle inventory (LCI) and life cycle assessment (LCA). Based on the material, it gives the user an idea on how it should be recycled. The goal for the Swiss Center for Life Cycle Inventories is to produce "a set of generic uniform and consistent LCI data of high quality" ("The ecoinvent Database", 2004). The database structure aids in life cycle assessments that give users an easier time in making decisions and looking over the descriptions in great detail. This database is closely connected with the "market (and consumption) situation" in Switzerland ("The ecoinvent Database", 2004).

Other countries surrounding Switzerland have a great impact on its economy and material extraction. Not all materials used in construction buildings come from Switzerland, but from other countries, which is taken in consideration in this ecoinvent database. Every country in the world has been included in this database. This database offers “average of technologies offered on the market today, the best available technology, (and) near future best available technology” (“The ecoinvent Database”, 2004). Pollutants and emissions from the past to the future are also calculated, “in relation to the time of operation/production” (“The ecoinvent Database”, 2004). There will be developments taking place to improve this database, such as “process(ing) datasets covering additional economic sectors, extension of energy, materials, transports, waste treatment datasets to other economies, additional impact assessment methods,” etc (“The ecoinvent Database”, 2004).

2.6 Limitations of LCA

LCA is a very complicated process; however, there are many software tools now available to help make thorough analysis easier and more consistent. Despite the various tools available, limitations of LCA remain. The process of conducting an LCA is very time consuming and requires many resources. Searching for data can be very difficult and the desired data may not be available. Using recent data is also very important as it can affect the accuracy of the assessment. It is important to consider the time and availability of data and funds against the benefits of the LCA. If the whole process of a product is considered, it is very time consuming and tedious.

How the system boundary is defined is also a limitation of LCA. For example, some cases include the transportation of all the materials. They may even go as detailed to include the fuel that the trucks run on or even the manufacturing of the trucks. However, in most cases LCA stops “before the capital goods” (Udo de Haes & Heijungs, 2007).

Saunders et al. (2013) held focus groups with members of the architecture, engineering, and construction communities to discuss why few whole building LCAs have been conducted. Figure 6 summarizes participants’ opinions regarding the limitations or barriers to the use of LCA in construction. The numbers in the parentheses are the number of times the barrier was stated in the discussion (Saunders et al., 2013). The most common limitation mentioned by participants was gaps in the method, such as the assumptions that are made and the inability to compare between product’s LCAs. Participants discussed other barriers such as logistical problems, gaps within the methods of LCA, educational problems, social problems, and economic problems. Other limitations that were identified were the lack of government incentives and results are difficult to interpret (Saunders et al., 2013). Rather than identifying one major, the discussion group identified factors that contribute to LCA’s limitations.

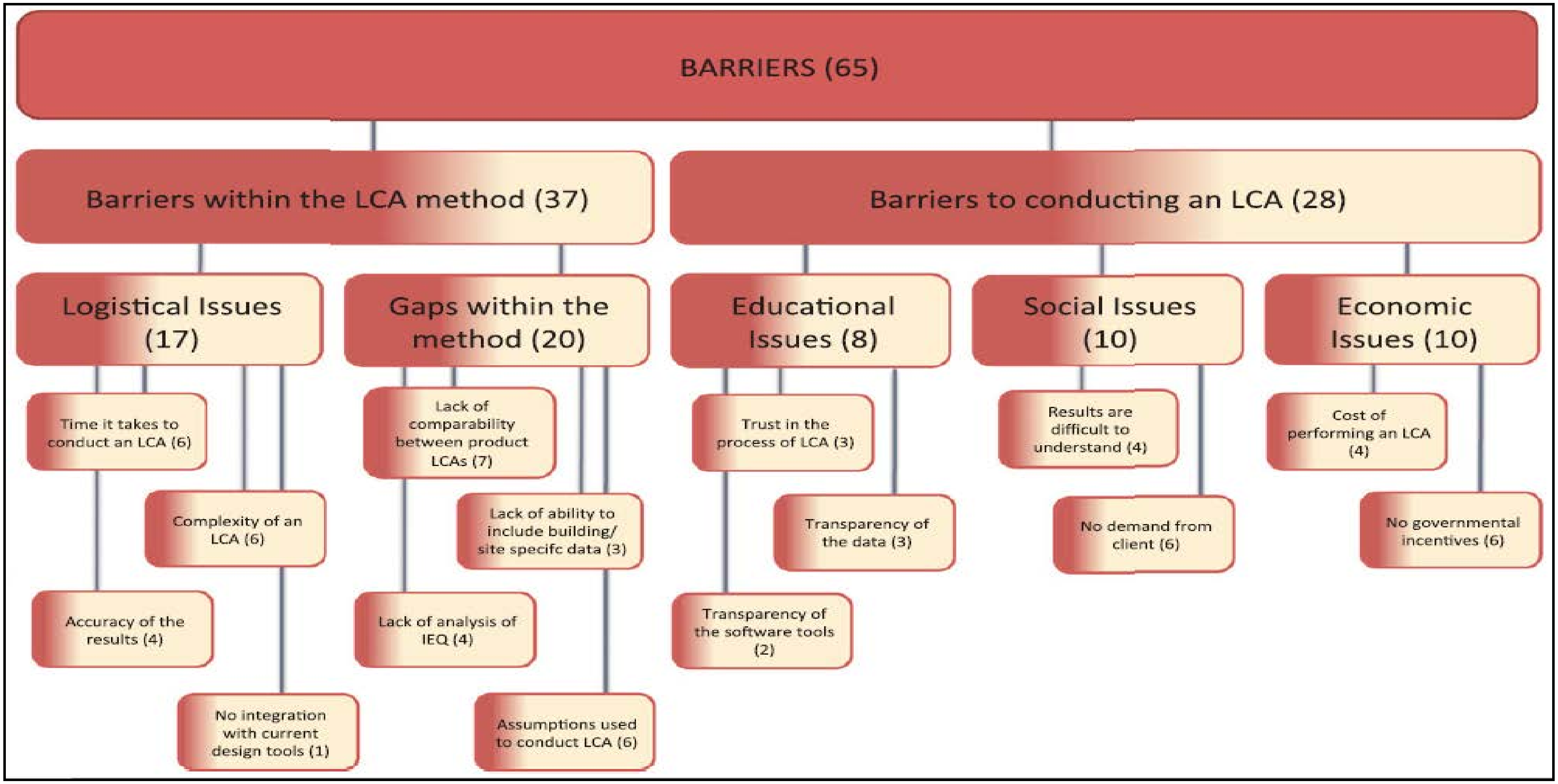


Figure 6. Limitations to LCA in the Construction of Buildings (Saunders et al., 2013).

2.7 HSLU's Interest in Solar Decathlon and LCA

The Lucerne University of Applied Sciences and Arts is competing in the Solar Decathlon competition for the first time in Versailles, France this June 2014. The Solar Decathlon competition in Versailles requires that participants use SimaPro® to determine and demonstrate the carbon footprint and sustainability of selected materials in their solar house. Our team is working with HSLU to evaluate how SimaPro® can best be used in this context.

The Solar Decathlon competition was developed in 2002 by the United States Department of Energy to challenge teams from universities all over the world to design and build a solar powered house that is energy efficient and cost-effective. The program is designed to encourage more sustainable building practices and to spread awareness about incorporating renewable energy in construction. Since its development, there have been six competitions that have occurred in the United States, Europe, and China ("SD China," 2013). Europe began hosting the competition in 2010, followed by China in 2013 (El-Korchi, personal communication, February 4).

For the competition, each team competes in a series of ten different contests: architecture, market appeal, engineering, communications, affordability, comfort zone, hot water, appliances, home entertainment, and energy balance ("U.S. Department of Energy- Solar Decathlon," 2014). Scores from each contest are summed and the winner is the team with the highest points out of 1000 possible. The United States Solar Decathlon website describes the winning team as one that produces a house that creates more energy than it consumes, supplies hot water as well as energy to power appliances and entertainment, is comfortable to live in, and affordable ("U.S. Department of Energy- Solar Decathlon," 2014).

The energy balance contest requires the house to generate as much or more energy than it consumes. In the 2013 competition in the United States, each team was given a bidirectional utility meter that measured the amount of energy the house produces and consumes to verify compliance ("U.S. Department of Energy- Solar Decathlon," 2014).

The Solar Decathlon competition is not a new concept to WPI. WPI competed in the Solar Decathlon in August 2013 and finished in 8th place out of twenty teams from various other countries. The team, called BEMANY, consisted of students from WPI, New York University Polytechnic School of Engineering, and Ghent University-Belgium. Students from the Worcester Technical High School helped construct the house ("Solar Decathlon China," 2013).

BEMANY chose the materials for their house based on speed of construction and efficiency. For example, the floors were made up of concrete tiles with phase changing materials. This choice of material was useful because the tiles capture thermal inertia and store it to release as needed (T. El-Korchi, personal communication, February 4). The team did not use any tools or databases to find information on the amount energy consumed in the production of materials. They only performed individual assessments of materials on an ad hoc basis. WPI's past involvement in the Solar Decathlon can be used to help recommend a process of approaching material selection for future HSLU teams to use.

LCA is a complex process and there is no uniform agreement on how it should be done. Practitioners approach it and establish system boundaries and assumptions differently. There are many new LCA tools available that lead to a range of standardization in approaches. However, each tool is different from the next in the way calculations are done and where the data on materials comes from.

The Solar Decathlon competition requires participants to use SimaPro®, even though it is not straight forward to use. HSLU requested help interpreting and using SimaPro® for the materials they are using in their y**our**⁺ house. The goal of our team was to determine the strengths and weaknesses of SimaPro® and to see if it can improve decision making about the choice of materials. This includes the assessment of whether it is better used to make materials selection in advance of construction or to justify material selection decisions after the fact. We also evaluated if there are simpler LCA tools that the HSLU team could utilize and how SimaPro® can best be used for decision making in the future.

3. Methods

The overall goal of this project was to assist HSLU in the development of systematic approaches for the selection of materials to be used in their current and future Solar Decathlon house projects. It was also to comment on the use of this type of assessment in sustainable construction.

This was completed by (1) assessing the best practices in life cycle assessment in the construction industries; (2) observing, documenting, and evaluating the decision-making process of the current Solar Decathlon house team in their materials selection; and (3) developing a user-friendly and functional guide to the SimaPro® software for future Solar Decathlon House teams. HSLU's team used the LCA program, SimaPro®, to analyze the materials already selected for their prototype and we determined if it is worth using for selection of concept materials. SimaPro® is a very complicated program with a steep learning curve and extensive instructional manuals that are difficult to figure out. We evaluated how well SimaPro® was suited to the needs of the HSLU team, and developed a simplified version of the existing training materials that better meets the needs and expertise of future teams.

We accomplished these objectives by using a variety of different approaches. We conducted further review of the literature, interviewed LCA experts in construction industries, interviewed HSLU faculty and students, and conducted focus groups with the HSLU Solar Decathlon team. We observed the team members as they finalized their construction options and material choices and documented their decision process. The interviews and focus groups informed us of the past decisions made for us to document.

3.1 Objective 1: An Assessment of Best Practices in LCA

Our preliminary research consisted of the analysis of different LCA databases to compare features. We researched key aspects of LCA, specifically in regards to the construction industry. To help us complete the goal of our project, we researched relevant terms to better understand the scope of our project. Such terms include LCA, sustainability, ecobalance, Minergie® and other key topics within our assignment. To do this we first needed to know the practices and process of a materials life cycle analysis. We focused our research on LCA to learn what it is, how it is conducted, and its limitations. We conducted thorough research on material and building life cycles from peer-reviewed journals, scientific articles and textbooks. Through background research, we familiarized ourselves with these environmental topics and how they impact the construction industry. In addition, the team studied modern sustainability practices in the construction industry, both in the United States and Switzerland.

In Switzerland, we interviewed academic professionals to supplement our findings from the literature review. Initial interviewees were identified by recommendations from our sponsors and further onsite research into specific individuals in sustainable construction studies. We developed a snowball sample by asking each interviewee for referrals to other experts in the field.

The preliminary step in conducting these interviews was to first contact them via email or phone to check their availability and willingness to talk to us. If they agreed to meet with us, we coordinated a time and place to converse. Appendix B contains a general script that we used while conducting these interviews. The questions changed as our research evolved and according to the interviewee's interests and expertise in the field. In general we asked about their perspectives on sustainability and use of LCA in materials selection.

3.2 Objective 2: Material Selection

It was important for us to understand what the HSLU team completed before we arrived and how they approached the material selection process. To accomplish this, we reviewed any available documents on the competition and SimaPro®. We then conducted focus groups with members of the HSLU team to understand their material selection process.

3.2.1 Review Documentation and Collaborate with HSLU Team

Prior to leaving the United States, our team reviewed HSLU's documents on their Solar Decathlon House as well as documents presented to each Solar Decathlon team by the competition organizers and SimaPro®. All of these materials were provided by Randy Cotten. Randy was a graduate student at HSLU, a member of the HSLU team, and was in charge of coordinating efforts between our group and the HSLU students and staff sponsors. We consulted with Randy and our sponsor liaisons, Professors Uwe Schulz and Shaun West. We developed a better sense of what the HSLU Solar Decathlon team achieved to date, what strategies they chose for design and materials selection, and the nature of their decision process.

The prototype house was a scale-model design to help the Solar Decathlon team visualize and verify material quantities. While interacting with students and faculty, we used our previously acquired knowledge of materials and SimaPro® to help us develop a model of their decision making processes for the selection of materials.

In addition, we developed a systematic approach towards the material selection process, and documented the approach HSLU had already been taking. Through face-to-face communication we tracked the previously completed material selection process, recorded the decision-making methods, and recommended alternative approaches. To do this accurately, we conducted interviews with students and faculty about previous decisions. We compared HSLU's design features with those of a similar team at WPI and benchmarked HSLU approaches against WPI's methodologies.

3.2.2 Focus Group

We conducted two focus groups with student participants of HSLU's Solar Decathlon team. The first of which was performed within the first few weeks of our arrival at HSLU. Randy Cotten provided us with a list of student participants we could contact. Due to the differing schedules of the students, we conducted informal discussions with a few students at a time. These focus groups enabled us to learn about the team's decision making process and how they chose which material was going to be installed. We wanted to understand their perspectives on LCA and how they implemented its practices in their decision making. In particular, we wanted to know how the SimaPro® tutorial had been used by Mr. Cotten, and how it could be improved upon for use by future students on similar projects. Appendix C contains general discussion topics for the focus group.

The focus groups were conducted on the HSLU campus. Forming a focus group was preferred over a survey because the group opened up more for discussion, allowing participants to actively share their ideas. It was important to keep in mind that there were more than 12 students on the team, so it was necessary to conduct more than one focus group. We approached student team members in person and asked if they would be willing to participate in a focus group to discuss their opinions about life cycle assessment, the materials they chose, and the Solar Decathlon house. We arranged meeting times for the focus group discussions. The location and meeting time was convenient to the participants in this focus group, often before team meetings or during lunch breaks. The participation was voluntary and the participants' responses were kept anonymous. No faculty were present for the purpose of creating a more comfortable environment for the students. Our team was open to positive and negative feedback in order to ensure honest evaluations of the process.

We decided to convene the first focus group shortly after our arrival in Switzerland so that the responses were fully analyzed and incorporated into the subsequent data gathering processes and analysis. We created a summary document for each focus group seen in Appendix F. The group collectively analyzed the results of each discussion.

3.3 Objective 3: A Guide to SimaPro®

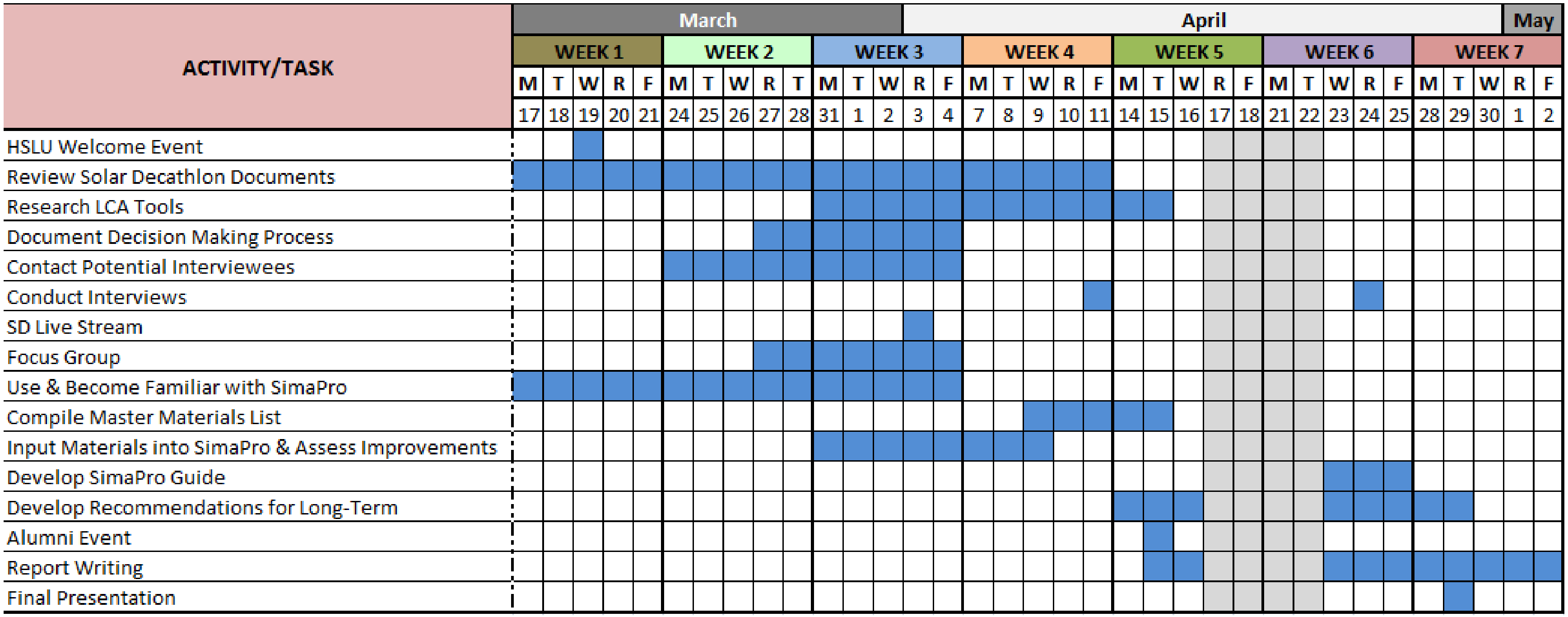
We conducted research on material selection, at the request of our sponsors at HSLU. Before traveling to Switzerland, we received the software download codes and installed it on our student-work laptop. We decided to lease a student-work laptop from WPI so that our documents as well as SimaPro® program would be in a central location for all to use. In addition, prior to our departure from WPI, we became familiar with the functionality and implementation of SimaPro® by completing the pertinent online tutorials.

Once established at HSLU, we received the appropriate database to run the program. This database is named SDE 2014 provided by the Solar Decathlon competition. Ecoinvent compiles the LCA data. At HSLU, Mr. Cotten was the sole user of SimaPro® and no members of the HSLU team had direct access to or experience with the software. After conducting the focus group, speaking with Randy Cotten and other SimaPro® users, and using the software ourselves, we identified the advantages and limitations of using SimaPro® for these kinds of construction projects. Throughout the project we documented shortcuts, tips and procedures that we found while using SimaPro®. Based on our findings, we produced a user-friendly and functional guide for future students who wish to use the SimaPro® software. You can access this document through the WPI database, titled SimaPro Guide (SimaPro Guide, Azizi, Love, Michalski, Tice, 2014).

In addition, we researched other LCA tools and examined their pros and cons. SimaPro® is complicated to use and we intended to discover if there are alternative decision making tools that are simpler to use. We performed a thorough literature review to research tools such as: The Building for Environmental and Economic Sustainability (BEES®), ATHENA® EcoCalculator, GaBi, Bauteil Katalog, and ATHENA® Impact Estimator. Figure 7 is our Gantt chart with dates we accomplished various tasks regarding SimaPro® as well as other project tasks.

3.4 Conclusion

By the projects' end, we made conclusions regarding the value of LCA in construction and of SimaPro® and other software as decision tools. Construction is a complicated process and we documented the decision points in the process of design and materials choices made by the HSLU team. We recommended how LCA could be better utilized in future projects as well as to what extent SimaPro® can play a role in this process. We recommended how design and materials choices could be made more efficiently and appropriately in the future. Through this steady and thoughtful methodology, we successfully obtained the information needed to thoroughly evaluate the team. Using our literature review and gathered knowledge, we reflected on these findings to create a set of recommendations found in the next section.



ACTIVITY/TASK	March													April																				May	
	WEEK 1					WEEK 2					WEEK 3					WEEK 4					WEEK 5					WEEK 6					WEEK 7				
	M	T	W	R	F	M	T	W	R	T	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F
	17	18	19	20	21	24	25	26	27	28	31	1	2	3	4	7	8	9	10	11	14	15	16	17	18	21	22	23	24	25	28	29	30	1	2
HSLU Welcome Event			■																					▨	▨	▨	▨								
Review Solar Decathlon Documents	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				▨	▨	▨	▨								
Research LCA Tools											■	■	■	■	■	■	■	■	■	■	■	■		▨	▨	▨	▨								
Document Decision Making Process									■	■	■	■	■	■	■									▨	▨	▨	▨								
Contact Potential Interviewees						■	■	■	■	■	■	■	■	■	■									▨	▨	▨	▨								
Conduct Interviews																				■				▨	▨	▨	▨		■						
SD Live Stream														■										▨	▨	▨	▨								
Focus Group									■	■	■	■	■	■	■									▨	▨	▨	▨								
Use & Become Familiar with SimaPro	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■									▨	▨	▨	▨								
Compile Master Materials List																		■	■	■	■	■		▨	▨	▨	▨								
Input Materials into SimaPro & Assess Improvements											■	■	■	■	■	■	■	■						▨	▨	▨	▨								
Develop SimaPro Guide																								▨	▨	▨	▨	■	■	■					
Develop Recommendations for Long-Term																					■	■	■	▨	▨	▨	▨	■	■	■	■	■			
Alumni Event																						■		▨	▨	▨	▨								
Report Writing																						■	■	▨	▨	▨	▨	■	■	■	■	■	■	■	■
Final Presentation																								▨	▨	▨	▨					■			

Figure 7. Gantt Chart of Tasks/Activities.

4. Findings

Our findings include team decision making, the materials selection process, and appropriate uses of SimaPro®. We observed the HSLU team in their decision making but our focus was on materials selection decision making and tools. First, we outline the composition of the Solar Decathlon team, describe their actual materials selection process, and then their approach to sustainability. Finally, we used our findings to propose a recommended materials selection process for future Solar Decathlon teams.

4.1 Team Selection, Composition, and Decision Making

The HSLU Solar Decathlon team was created through a selective process. Most of the students participated in a formal application process and were accepted into the team after a rigorous evaluation. A small number of students were recruited directly by faculty prior to and during the project based upon their particular skills, training and talents. If the team lacked a specific ability, and professors knew a student that was proficient at this task, they were selected. This resulted in roughly seventy students who worked on the project at some point or another and ten professionals working on the construction house on site. Of the seventy, thirty to forty were invested every day in advancing the project and meeting deadlines. A smaller number invested their entire academic and free time to ensure the success of the project. A number of architects spent in excess of twelve hours a day for several weeks prior to and during our time at HSLU in order to meet deadlines and produce quality products.

The HSLU team was interdisciplinary and included students majoring in architecture, interior design, building engineering, business engineering, computer science, electrical engineering, and mechanical engineering. Small groups of students within the same disciplines took responsibility for certain aspects of the y**our**$^+$ house. For example, the largest specialized group comprised entirely architects and another group of electrical and mechanical engineers focused on the HVACS (Heating Ventilation Air-Conditioning Sanitary) systems. Within the HVACS team particular individuals took responsibility for one component (i.e. heating or air conditioning, or ventilation, or sanitary systems). In addition, other groups were dedicated to Information Technology, Business Engineering, Design and Art, and Building Engineering. In order to try to unite all team's efforts in an orderly fashion, a member from each specialized team, was chosen to serve on the Communications team.

The leadership evolved after a semester of work. In the Fall Semester (2013), leadership shifted from faculty to students who demonstrated the most developed and appropriate group and project management skills. This shift led to clear definitions of roles by the Spring Semester (2014), resulting in more proficient task management. Marcel Wyss, a graduate student, rose as a clear leader whom everyone respected and trusted. A few tasks of many of his responsibilities were to run weekly team meetings and track submittal dates (see Appendix G). Without Marcel, teammates concluded that the team would not have had a clear direction and deliverables would not have been completed in an orderly and timely manner. The HSLU Solar Decathlon team had a hard copy of their schedule posted in their work office, but most referred to a daily-updated one on the server.

4.2 HSLU's Performed Material Selection Process

We outlined HSLU's actual material selection process in Figures 8 and 9. It is broken down into three phases: Design, Construction, and Review. These phases are color coded in black, blue, and red respectively. During the Design Phase, attention towards materials was spilt into two categories: basic and essential. Once there was agreement, the process continued with the Construction Phase. The intentions of the team switched towards the Review Phase once quantities were refined. There were two parallel processes, the material review as well as continued construction. Their Review Phase concluded with the selection of alternative materials for the concept house.

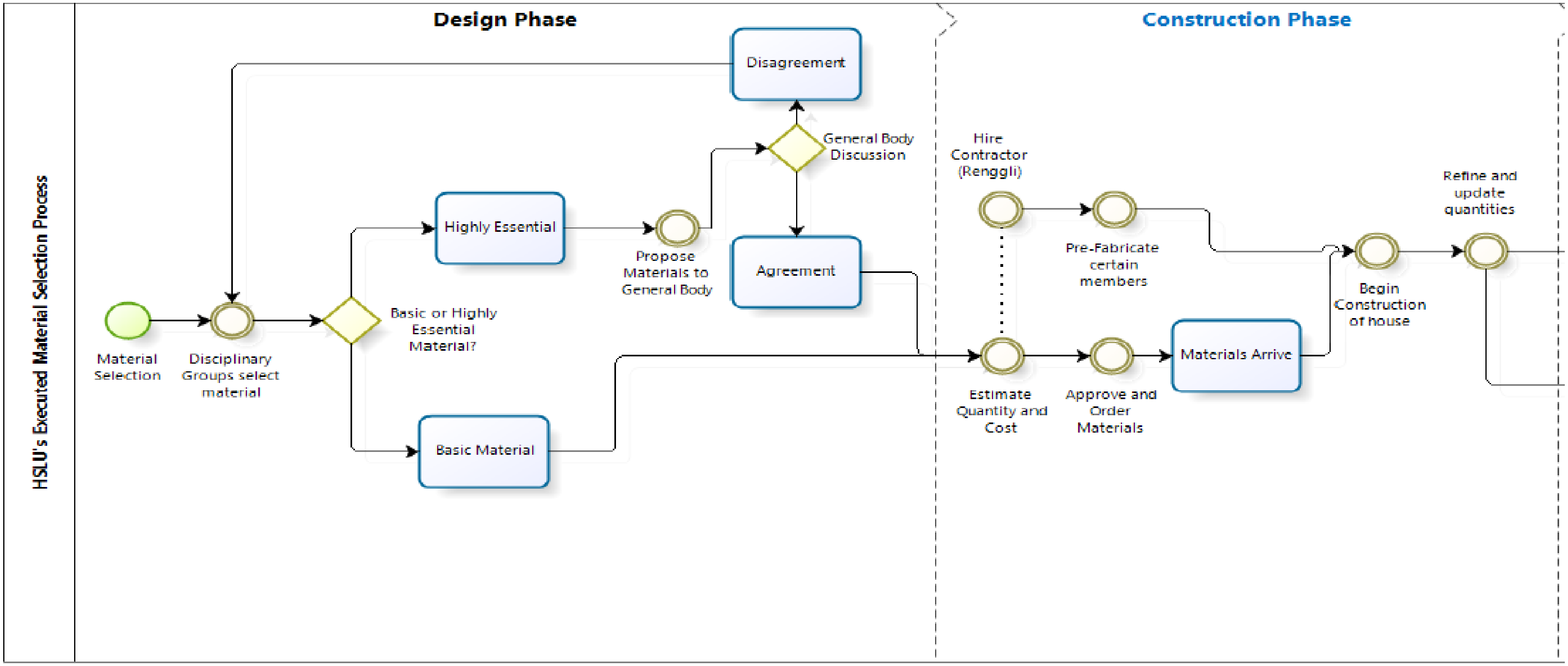


Figure 8. HSLU's Executed Material Selection Process Part 1.

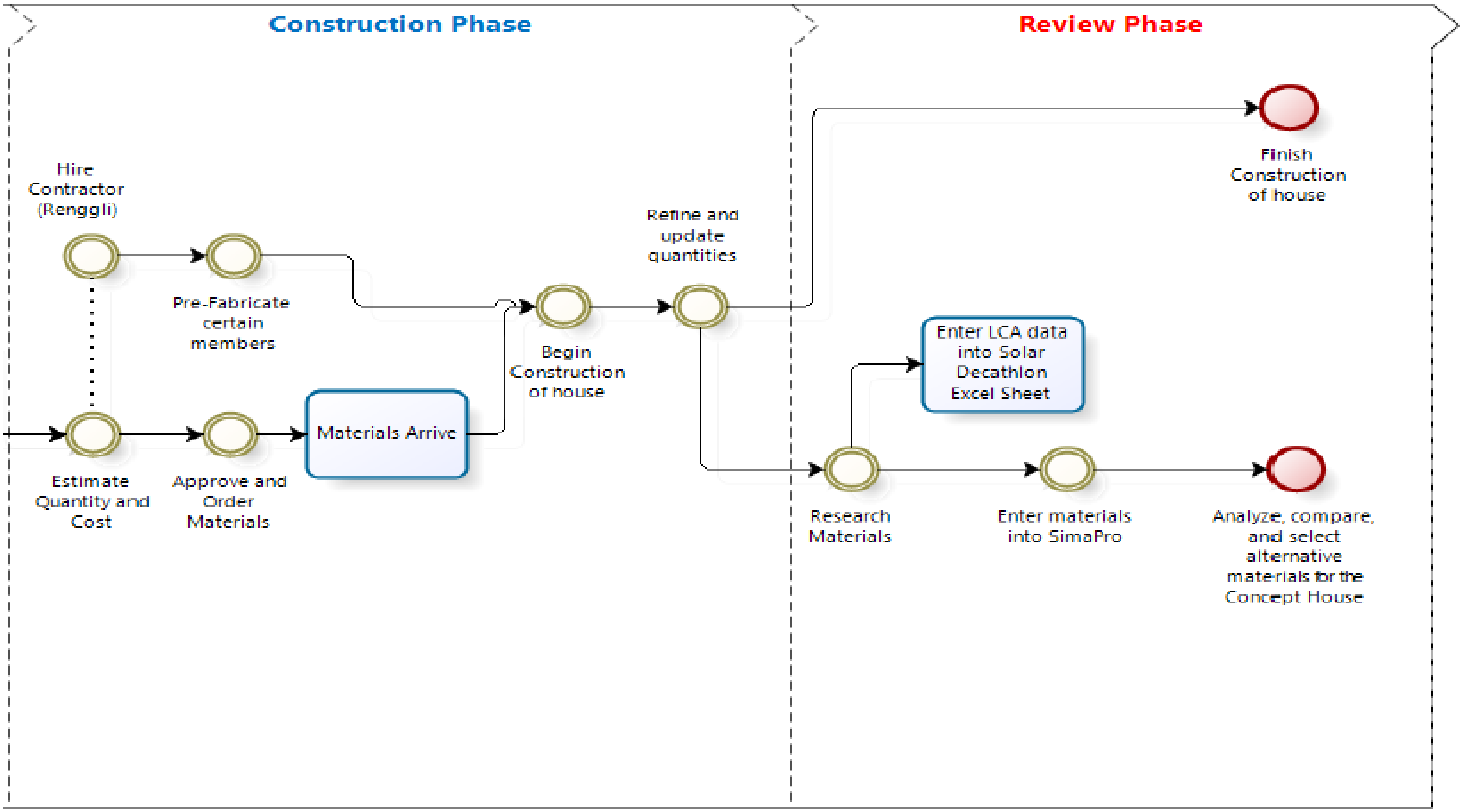


Figure 9. HSLU's Executed Material Selection Process Part 2.

4.2.1 Design Phase

During the Design Phase (Figure 8), which was before our arrival in Switzerland, the HSLU team focused on sustainability at the macro-scale. Thus, they developed the design concept of shared space as a way to reduce materials in construction and energy use during operation. Accordingly, they did not focus on material selection as a means of micro-sustainability during the Design Phase. Investigation of SimaPro® or alternative software did not occur at this point, limiting material selection only to the students' knowledge and experience. During the Design Phase, as pictured in Figure 8, attention towards materials was split into two categories.

Central to each small disciplinary student group was basic material selection. After a brief review of the materials, the HSLU team chose the materials that received the most support from the entire team at the weekly team meetings. When the team fully agreed on the materials, the Construction Phase began. If there was disagreement on materials, then the small disciplinary group reviewed it and proposed an alternative material to satisfy the majority or support their previously chosen material. This cycle sometimes revolved several times. When established Solar Decathlon competition deadlines approached, Marcel made an 'executive' decision on materials to begin quantity and cost estimation.

The majority of the material selection was conducted by the HVAC and Architecture groups. We first spoke with Roger Hauswirth, who is a mechanical engineer, and in the HVAC group and Fiona Berger, who is an architect on the team. The HVAC group chose materials based on the overall efficiency of the system and not necessarily how sustainable each individual material is in the system. The importance of the system functionality was placed higher than sustainability because of space limits, electrical requirements, and heating and cooling capacities. In some cases the HVAC group had no choice about which material to select because the particular system was only available in one material. For example, they had no choice but to use stainless steel for the ventilation system and polyethylene for the water collection system.

The architects selected materials based on the texture and aesthetics of the materials prior to researching material composition. They wanted to ensure each material would look attractive in the completed house and were not initially concerned about the sustainability of the materials chosen. After narrowing the options down, they then focused on the composition of each material based on information provided by the company that manufactures the material.

4.2.2 Construction Phase

We were on the construction site and documented the team's work for the majority of the Construction Phase. To begin our definition of the second phase, the HSLU team decided on both the basic materials and essential materials. Basic materials were standard materials (e.g., insulation) for which there are few available alternatives and about which there was little disagreement among team members. Essential materials, such as the flooring in the house, were very contentious and the HSLU team spent much time arguing about the relative merits of the alternatives. The essential materials also had large impacts on the house's overall sustainability.

Rough estimates of the quantity and cost associated with each material were made by each disciplinary group. Wood and foundation materials were ordered in bulk in excess of expected needs with the intention of returning the extra. Renggli, the contractor of choice for HSLU, was then hired to start working on the pre-fabrication for the house. Deployment of the contractor was delayed until this point in the process to ensure there was enough work for them. After the quantities and cost estimates were submitted by the specialized groups, they were approved by the team leaders before the specialized group ordered them. The team did not request Renggli to choose specific kinds or sources of wood to maximize sustainability. Instead they deferred to the contractor and let him use the types and sources of wood he preferred and would ordinarily use. The team assumed that the Swiss standards of materials procurement were high enough to meet the sustainability criteria of the competition. Once fabrication started and items arrived on the job site, the HSLU team recorded quantities and shipped excess materials back to the supplier.

4.2.3 Review Phase

We participated heavily in HSLU's Review Phase (Figure 9) of their material selection process. Collaboratively with the sustainability group, we edited and added information to the lengthy submittal titled the Sustainability Report. This report was used to justify the technologies they selected for their house on both the macro- and micro-scale. In addition, part of the Review Phase was SimaPro® entry and analysis as a means to propose alternative materials for the concept house.

Sustainability Report

The Solar Decathlon competition required all teams to write a report that describes the elements of the house that contribute to its sustainability. The competition rules required that the report should present arguments based on economic, social, and environmental issues. The rules also described the specific sections which the document should contain. They include: general concept of the project and sustainability, urban design, bioclimatic strategies, construction system, materials, active systems, solar systems, water, solid waste, and life cycle analysis. The sustainability report was a major component of the competition, on which each team was evaluated. Before the competition began in Versailles, France, each team was required to submit several drafts of their sustainability report and received detailed comments and suggestions for improvements from the judges.

The HSLU Solar Decathlon team had several team members write the report together. To do this, a Google document was created and shared between the team members contributing to this report. This allowed multiple students to work on the report at the same time and ensured that each person was working on the most up-to-date document. The competition requires that the sustainability report be written in English. Some of the students on the HSLU team that were writing it, however, were not native English speakers. In addition to his other responsibilities, Randy Cotten, who was originally from America, aided in checking over the report before it was submitted.

Our team reviewed the report before and after it was sent to the Solar Decathlon committee for review. Before it was sent, we gained access to the document via their Google account where we made comments on the report's content and grammar. After the detailed feedback was received from the committee, we reviewed the document a second time. This time we went through the judges' comments and made suggestions on the Google document on the content that was missing. Using Google drive to work on the report was very beneficial to the HSLU team and streamlined the process. It ensured that there was only one version of the document.

Our team learned interesting features of the HSLU team's strategies to win the competition while reading the Sustainability Report. The collection of rainwater was optional according to the Solar Decathlon rule book. However, the team designed the house to include appliances that have rain water adaptors, which is typical for Switzerland. For example, the rain water collected was used for the first cycles of a wash machine to soak the clothes, and then fresh water was used for the cleaning portion. Another strategy was reusing grey water. Waste water from bathroom sinks was collected in the toilet reservoir for flushing the toilet. In addition, hot water from the shower was designed to heat copper coils under the shower floor which in turn help heat the fresh water going to the shower head. These creative innovations gave HSLU an advantage in the 2014 Solar Decathlon competition.

The team chose the most efficient solar panels to install in their y**our**$^{+}$ house. The rules stated that the peak power produced by all of the solar panels should be no more than 5 kW. They researched the best panels on the market and mounted them onto the prism boundary located on top of the house within the solar envelope. With only a maximum of 150.0 square meters for the architectural footprint, the final design was developed from the inside out. Specific elements of the house were developed first including floor plans of the three individual rooms, then the floor lay out of the space+ combined with all rooms. The architectural team created a design modeled after the idea of 'urban design'. Urban design allows for many people to live in a small area while leaving room, as private areas, for themselves. By creating *your room, my room,* and *our room*, there was flexibility of living for any person (Figure 10). Space+ design was created with the purpose of connecting the three previously mentioned rooms. The architects wanted light to make the hallways appear bigger. The downside of this is that the transmittance of light and associate solar gain would require a larger capacity ventilation system to keep the house cool. The architects and the HVAC team had to negotiate a common design that would achieve the desired natural lighting levels and an appropriate ventilation system.

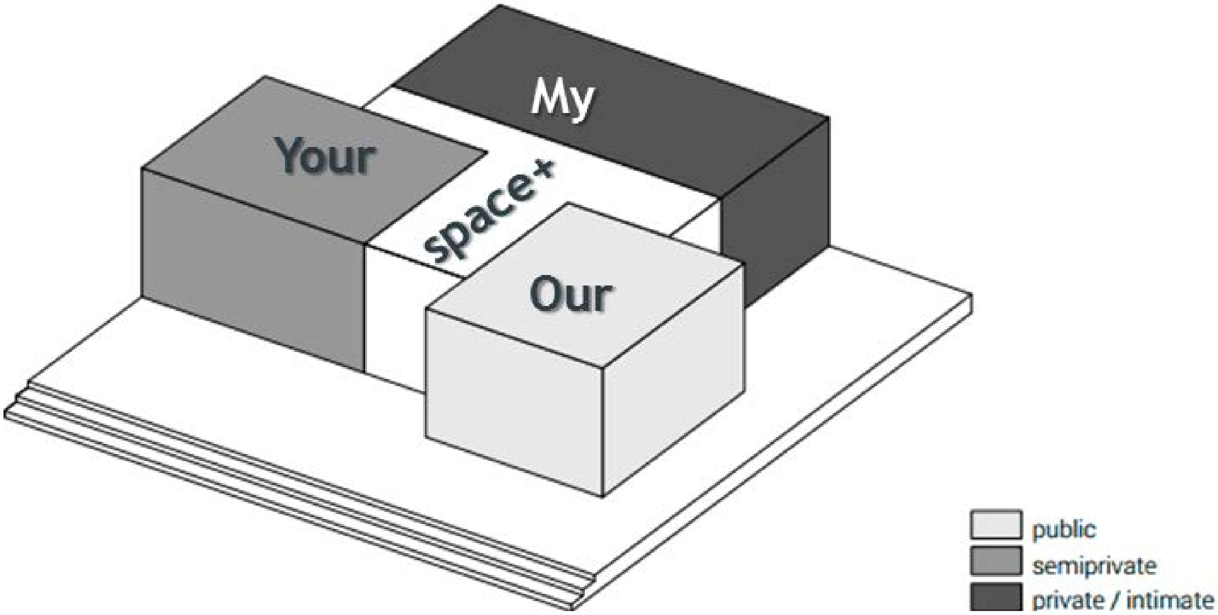
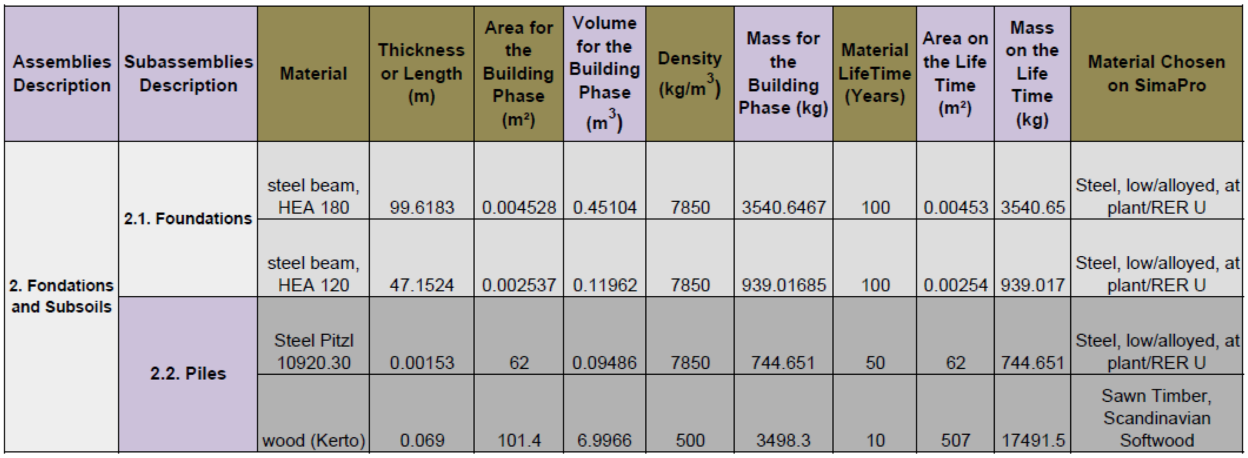


Figure 10. Shared Space Concept for the your$^+$ Prototype.

Material Research

The Solar Decathlon competition requires a detailed list of all materials that are used in each house. This included all materials used in the creation, transport, operation and proposed demolition. We created this master materials list of over 250 materials, part of which is displayed in Figures 11, 12, and 13, for the HSLU team which coincided with our research of the team's material selection process. Mr. Cotten relied on our team to collect, research, and calculate the various entries for this list. In the competition guidelines, the Solar Decathlon Committee provided each team a Microsoft Excel™ template. Each material was organized by its future assembly grouping such as foundation/sub-structure, roofing and sheathing, and doors and openings. For example, under the Foundation and Subsoils section, kerto wood, low alloyed steel beams (HEA 180 and 120) and steel pitzl (adjustable steel footings used for precise leveling) were all used. For each material in this master list, we collected a wide range of data. The most important data columns that we calculated were Mass for the Building Phase, Way of Travel from Manufacturer, and End of Life Scenario (Figures 11, 12, 13). These columns were the most important because their values impacted the SimaPro® analysis.



Assemblies Description	Subassemblies Description	Material	Thickness or Length (m)	Area for the Building Phase (m²)	Volume for the Building Phase (m^3)	Density (kg/m^3)	Mass for the Building Phase (kg)	Material LifeTime (Years)	Area on the Life Time (m²)	Mass on the Life Time (kg)	Material Chosen on SimaPro
2. Fondations and Subsoils	2.1. Foundations	steel beam, HEA 180	99.6183	0.004528	0.45104	7850	3540.6467	100	0.00453	3540.65	Steel, low/alloyed, at plant/RER U
		steel beam, HEA 120	47.1524	0.002537	0.11962	7850	939.01685	100	0.00254	939.017	Steel, low/alloyed, at plant/RER U
	2.2. Piles	Steel Pitzl 10920.30	0.00153	62	0.09486	7850	744.651	50	62	744.651	Steel, low/alloyed, at plant/RER U
		wood (Kerto)	0.069	101.4	6.9966	500	3498.3	10	507	17491.5	Sawn Timber, Scandinavian Softwood

Figure 11. Part of the Material Information Section of the Master Materials List for the your$^+$ House.

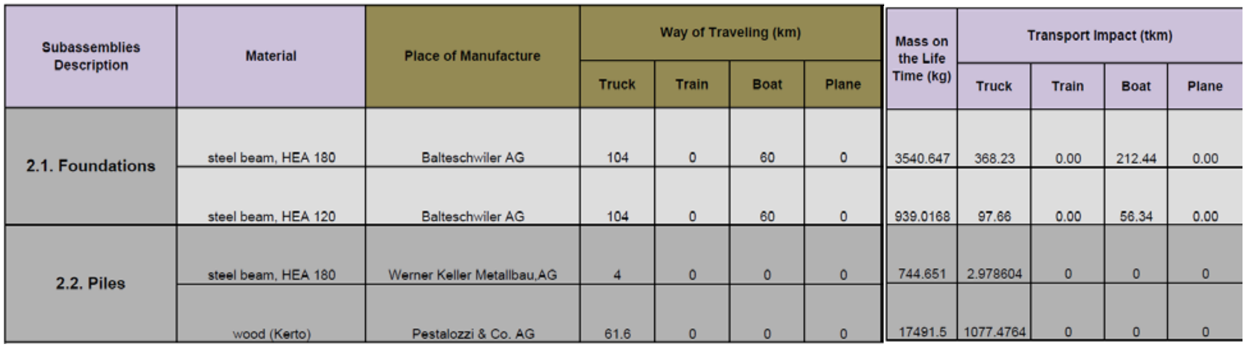
First, the material information in the table is broken down into the general material information which includes the industry name of the material. This column presented unforeseen complications because the industry names of materials, such as steel, are different between countries even though the process to make them and the compositions are the same. In order to minimize confusion, we included each company or the custom name used in the industry in this column. It was recorded in the “Material Chosen on SimaPro®” column as the same material to document the choice.

Moving along the next two columns were “Thickness or Length” measured in meters, and “Area for the Building Phase” measured in square meters. We completed both of these columns by looking at shipping invoices from the company to the construction site. Unfortunately, the HSLU team rarely had the records readily available or stored in a single database. As a result, piecing together this information took us a considerable amount of time and perseverance. The quantities that were ordered in excess were reduced to the amount that was used for the house. These two columns were, however, crucial in calculating the volume for the building phase which is calculated by multiplying the “Thickness or Length” and “Area for the Building Phase”, as expressed in cubic meters. Following area we took into account Density and Mass for the Building Phase.

After researching the densities of the material in construction manuals and Swiss industry standard guides, they were multiplied with the Volume to yield the Mass for the Building Phase.

Following this is the part of the materials information in regard to its lifetime. The Solar Decathlon requires standardized buildings with a 50 year lifetime. The Area on the Lifetime and Mass on the Lifetime columns include adjustments based on whether or not a material has an expected lifetime shorter or greater than 50 years. For example, kerto wood only has a lifetime in the subsoil of a building of ten years. Instances such as this one require the mass and area on the lifetime to be multiplied by five.

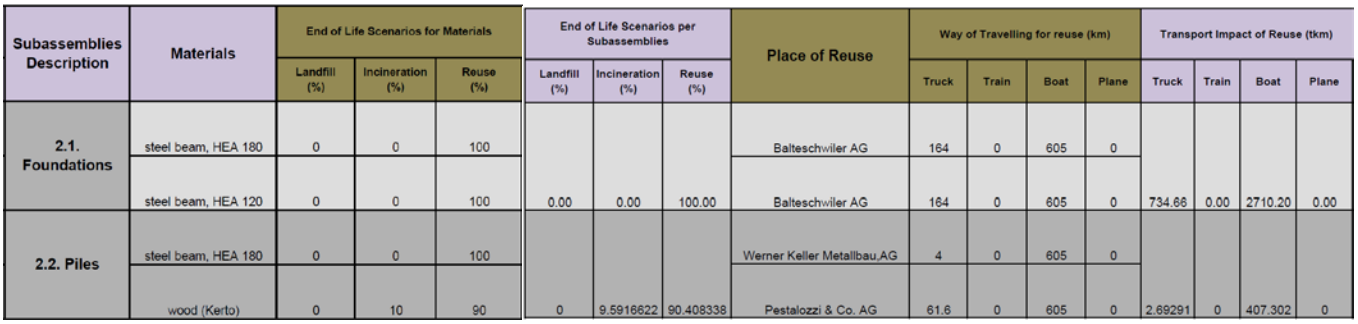
Data on the transportation of materials was difficult to obtain because the HSLU team did not define the required parameters. Parameters for LCA include the selected beginning and end of life. The granularity for transport over a material's life cycle is limitless. Granularity is the extent to which a system is subdivided, increasing as the level of detail rises. In consultation with the HSLU team, we agreed to trace the transport of each material back to the place of manufacturing and not go back as far as the point of harvesting. This is because we could not readily obtain all of that information from the production industries due to misplaced information, general lack of knowledge and time constraints. Suppliers often do not have the information required for a thorough analysis. Therefore the information displayed in the Transport section (Figure 12) is the total distance the material traveled from the manufacturer to the HSLU campus and the mode of transportation used. These distances were established from geographical research online. The environmental impacts associated with each mode of transportation (truck, train, boat, plane) are substantially different when analyzed in SimaPro®, which is why we used four categories and not just total distance. Transport impact is a more precise way to measure the impact of transporting materials since it also accounts for the weight of the materials transported as well as the mode of transport and distance traveled. Heavier materials require more fuel to ship than lighter materials and have greater impact on the environment and overall ecobalance of the material.



Subassemblies Description	Material	Place of Manufacture	Way of Traveling (km)				Mass on the Life Time (kg)	Transport Impact (tkm)			
			Truck	Train	Boat	Plane		Truck	Train	Boat	Plane
2.1. Foundations	steel beam, HEA 180	Balteschwiler AG	104	0	60	0	3540.647	368.23	0.00	212.44	0.00
	steel beam, HEA 120	Balteschwiler AG	104	0	60	0	939.0168	97.66	0.00	56.34	0.00
2.2. Piles	steel beam, HEA 180	Werner Keller Metallbau,AG	4	0	0	0	744.651	2.978604	0	0	0
	wood (Kerto)	Pestalozzi & Co. AG	61.6	0	0	0	17491.5	1077.4764	0	0	0

Figure 12. Part of the Transport Section of the Master Materials List for the your$^+$ House.

Finally, we also recorded the end of life scenarios (Figure 13). Our group found this to be the hardest section to complete. This section includes what form of disposal methods will be used for the materials and their subassemblies, place of reuse, transport of reuse and transport impact during reuse. Based on data provided by the disposal company and the location of their final disposal, we calculated the percentages of the materials masses that would either be landfilled, incinerated or reused. Better options for disposal methods can be investigated with the compilation of transport impact calculations. The purpose of the materials data sheet was to be able to input data seamlessly into SimaPro® for analysis.



Subassemblies Description	Materials	End of Life Scenarios for Materials			End of Life Scenarios per Subassemblies			Place of Reuse	Way of Travelling for reuse (km)				Transport Impact of Reuse (tkm)			
		Landfill (%)	Incineration (%)	Reuse (%)	Landfill (%)	Incineration (%)	Reuse (%)		Truck	Train	Boat	Plane	Truck	Train	Boat	Plane
2.1. Foundations	steel beam, HEA 180	0	0	100	0.00	0.00	100.00	Balteschwiler AG	164	0	605	0	734.66	0.00	2710.20	0.00
	steel beam, HEA 120	0	0	100				Balteschwiler AG	164	0	605	0				
2.2. Piles	steel beam, HEA 180	0	0	100	0	9.5916622	90.408338	Werner Keller Metallbau,AG	4	0	605	0	2.69291	0	407.302	0
	wood (Kerto)	0	10	90				Pestalozzi & Co. AG	61.6	0	605	0				

Figure 13. Part of the End of Life Section of the Master Materials List for the your$^+$ House.

SimaPro® 7.3.3

A major component of the Solar Decathlon competition was to utilize the Life Cycle Assessment (LCA) tool, SimaPro®. It states in the official rule book "Teams must read and follow the instructions of the TEE (Thermal and Environmental Evaluation) Information Guide" (SD 2014). In the TEE, a SimaPro® template was provided. The template was intended to help teams learn the SimaPro® program and input their materials selection data precisely and appropriately. The HSLU team nominated their head sustainable engineer, Randy Cotten, to take lead on the SimaPro® evaluation of the project. Randy followed the TEE guidelines and template closely and eventually relied on our team entirely to input the materials data and analyze them in SimaPro®. The team did not use SimaPro® as a tool to select materials. Instead, we used it to assess the products they had chosen previously for their prototype house. We provided the HSLU team with comparisons between the materials they had chosen and possible alternative materials that they might use in the proposed concept structure[1].

During our preliminary research in Worcester, we believed our project goal was to evaluate HSLU's use of SimaPro® and recommend potential improvements for using the software in the future. However, over the course of our time at HSLU our project shifted more to the task of completing the SimaPro® evaluation of their chosen materials to justify their decisions and identify alternative materials for the concept structure. Accordingly, we selected composite data on materials for entry into SimaPro® by cross fertilizing the information given by the SDE Template, the ecoinvent database, and the information we had collected in the master materials list.

These set of comparisons between chosen materials for the prototype house used in the competition and the large scale proposed concept housing complex was one of our final deliverables. We provided the HSLU team with three different material comparisons. These justified which materials they used for their prototype home and how they differ from the materials that the concept home will be constructed with. The first comparison we calculated was for the foundation construction material, we compared the low-alloyed steel against a common poured concrete. Secondly, super structure composition was evaluated. We took the three types of woods that were used in the prototype and compared them to concrete blocks to show the impact each material has on its own instead of in a composite wall. Lastly, the choice of insulation was analyzed because of its large contribution to the overall sustainability within the home. We decided to take into account the rock wool, which was the chosen material, and compare its environmental sustainability to that of glass wool mat, cellulose fiber, and urea formaldehyde foam.

Figure 14 shows the impacts associated with the use of steel versus concrete in the foundation. The HSLU team chose to use steel for the foundation of the prototype but we explored whether concrete might actually prove to be a more 'sustainable' alternative.
Using SimaPro®, we entered the amount of low-alloyed steel that was selected for the foundation (in kilograms) in the prototype and compared it with the amount of poured concrete needed for a building with the same structure. The SimaPro® software computes the energy used, and

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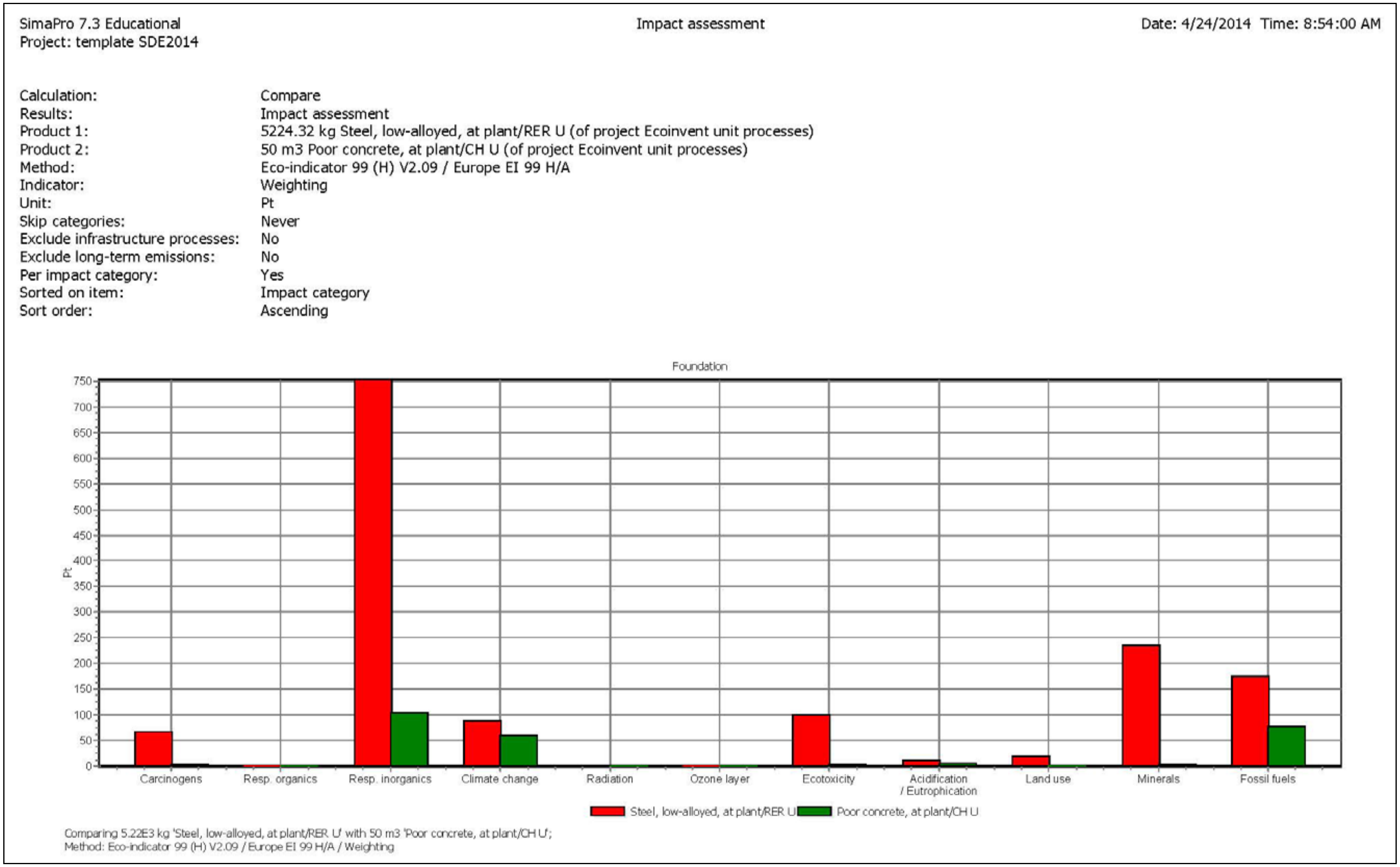
[1] The Concept House was a proposed model presented in the Solar Decathlon competition. The submitted structure, the y**our**+ prototype, was one module. Several of these models grouped into one complex was the Concept.

emissions released during each of the life cycle processes for a given material. This information was then displayed in the comparisons broken down into eleven main categories: carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone production, eco-toxicity, acidification, land-use, mineral consumption, and fossil fuel production. Figure 14 illustrates that the poured concrete has less of an environmental impact than steel. This is because the graph shows that steel produces more fossil fuels, respiratory inorganics and carcinogens than concrete. Therefore concrete has less of an environmental impact and because they have the same lifespan, concrete is more sustainable as well.



SimaPro 7.3 Educational
Project: template SDE2014

Impact assessment

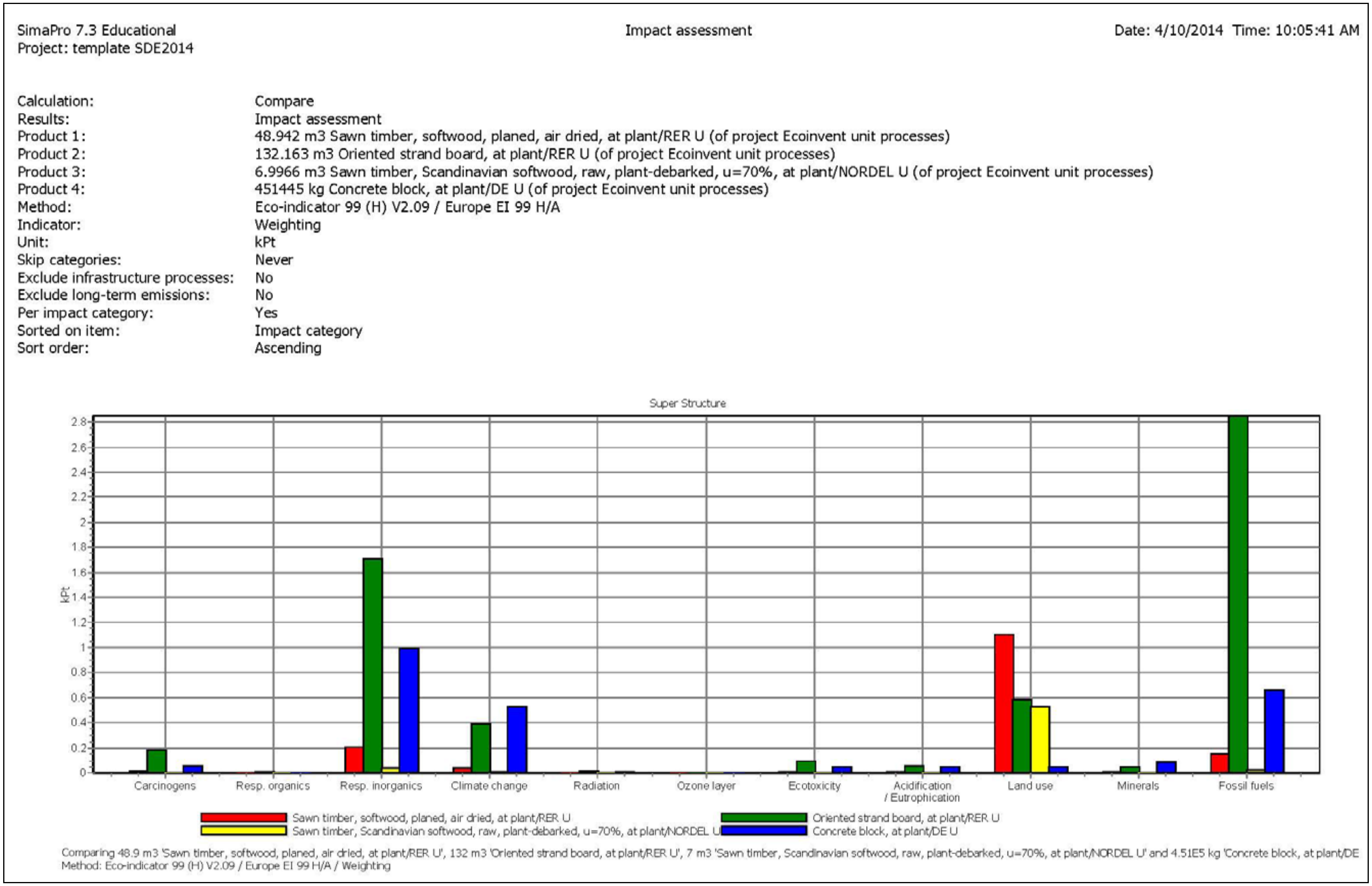
Date: 4/24/2014 Time: 8:54:00 AM

Calculation:	Compare
Results:	Impact assessment
Product 1:	5224.32 kg Steel, low-alloyed, at plant/RER U (of project Ecoinvent unit processes)
Product 2:	50 m3 Poor concrete, at plant/CH U (of project Ecoinvent unit processes)
Method:	Eco-indicator 99 (H) V2.09 / Europe EI 99 H/A
Indicator:	Weighting
Unit:	Pt
Skip categories:	Never
Exclude infrastructure processes:	No
Exclude long-term emissions:	No
Per impact category:	Yes
Sorted on item:	Impact category
Sort order:	Ascending

Comparing 5.22E3 kg 'Steel, low-alloyed, at plant/RER U' with 50 m3 'Poor concrete, at plant/CH U';
Method: Eco-indicator 99 (H) V2.09 / Europe EI 99 H/A / Weighting

Figure 14. SimaPro® 7.3.3 Impact Assessment of Low-alloyed Steel vs. Poured Concrete.

Figure 15 shows the impacts associated with the use of concrete block versus multiple types of wood for the super-structure. The HSLU team chose to use wood materials for the super-structure of the prototype but we explored whether concrete block might actually prove to be a more ‘sustainable’ alternative. This was a crucial decision in the design process of the house because the house ended up being made almost entirely of wood. The HSLU team decided that wood is easy to transport, readily available in the region and most efficient when it comes to time sensitive construction which pertains directly to the solar decathlon competition. Using SimaPro®, we entered the amounts of each type of wood selected for the super-structure (in cubic meters) in the prototype and compared it with the amount of concrete block needed for a building with the same structure. Contrary to popular belief concrete blocks, also known as cinder blocks, will have less of an environmental impact compared to sawn timber and dry wall when used for a base wall material. The Figure 15 shows that the oriented strand board (OSB or dry wall), represented in green, has an extremely large impact on the environment throughout its production. Specifically the fossil fuel production is much more when compared to the sawn timber and concrete blocks.



SimaPro 7.3 Educational
Project: template SDE2014

Impact assessment

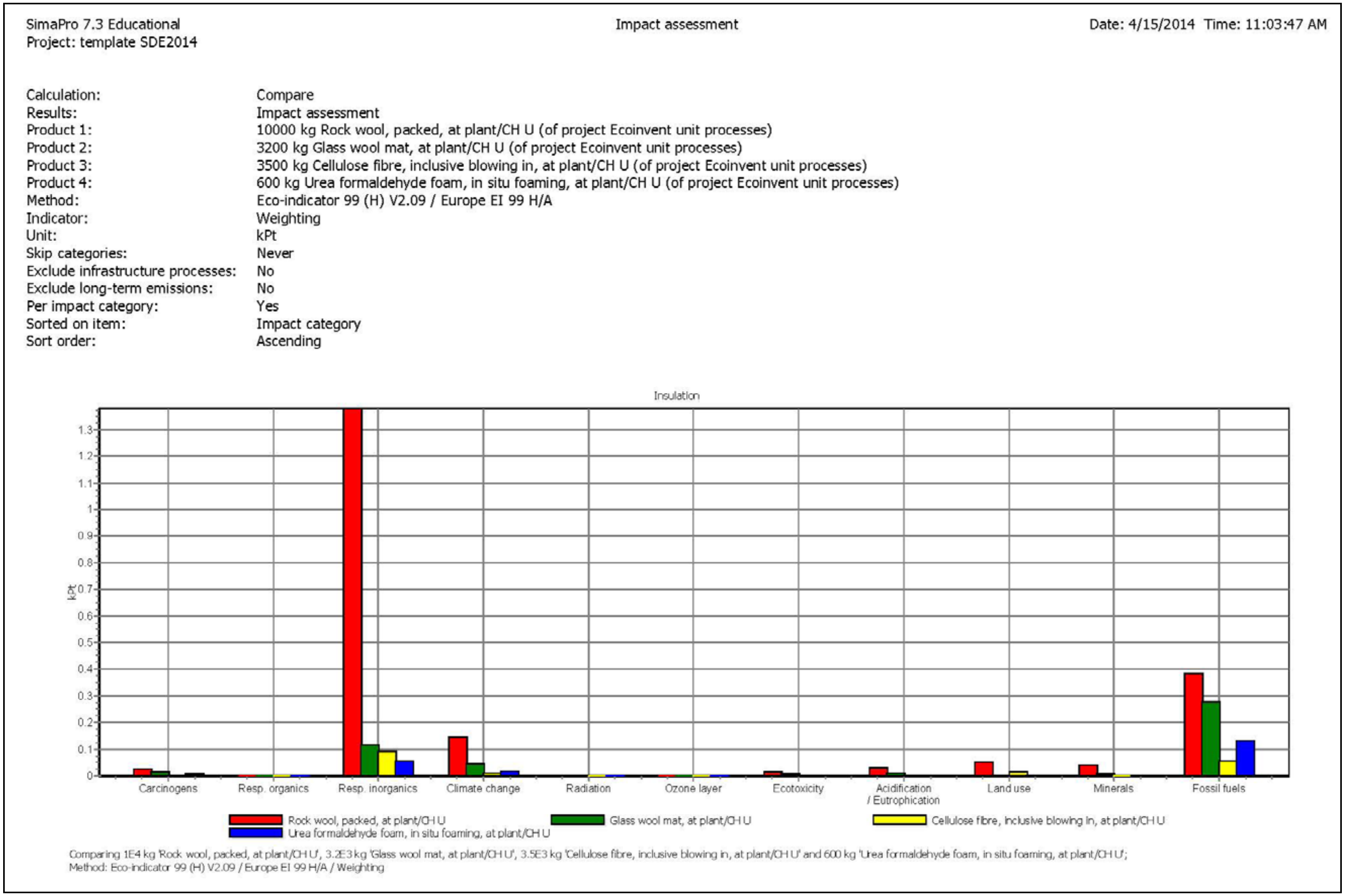
Date: 4/10/2014 Time: 10:05:41 AM

Calculation: Compare
Results: Impact assessment
Product 1: 48.942 m3 Sawn timber, softwood, planed, air dried, at plant/RER U (of project Ecoinvent unit processes)
Product 2: 132.163 m3 Oriented strand board, at plant/RER U (of project Ecoinvent unit processes)
Product 3: 6.9966 m3 Sawn timber, Scandinavian softwood, raw, plant-debarked, u=70%, at plant/NORDEL U (of project Ecoinvent unit processes)
Product 4: 451445 kg Concrete block, at plant/DE U (of project Ecoinvent unit processes)
Method: Eco-indicator 99 (H) V2.09 / Europe EI 99 H/A
Indicator: Weighting
Unit: kPt
Skip categories: Never
Exclude infrastructure processes: No
Exclude long-term emissions: No
Per impact category: Yes
Sorted on item: Impact category
Sort order: Ascending

Comparing 48.9 m3 'Sawn timber, softwood, planed, air dried, at plant/RER U', 132 m3 'Oriented strand board, at plant/RER U', 7 m3 'Sawn timber, Scandinavian softwood, raw, plant-debarked, u=70%, at plant/NORDEL U' and 4.51E5 kg 'Concrete block, at plant/DE
Method: Eco-indicator 99 (H) V2.09 / Europe EI 99 H/A / Weighting

Figure 15. SimaPro® 7.3.3 Impact Assessment, 3 Wood Products vs. Concrete.

We performed an additional comparison between the material chosen for insulation (rock wool), and three other types of insulation (glass wool, cellulose fiber or urea formaldehyde foam) (Figure 16). The HSLU team chose to use rock wool for insulation of the prototype but we explored other options because the amount of rock wool needed to insulate greatly exceeds (in kilograms) the other three options. HSLU decided to choose rock wool because it is easily purchased in large quantities, is close to the construction site in Luzern, and is the type of insulation usually used by the contractor, Renggli. Using SimaPro®, we entered the amount of rock wool that was selected for the prototype and compared it with similar quantities of the other insulators. From the impact assessment of possible insulations shown below, we concluded that any of the possible types of insulation can be used. Relative to the wood in the walls and the steel for the foundation, the rock wool has little to no impact on the environment or overall sustainability of the house. The chart shows that the urea formaldehyde foam has the least amount of environmental impacts. Therefore it would be the best option for insulation.



SimaPro 7.3 Educational
Project: template SDE2014

Impact assessment

Date: 4/15/2014 Time: 11:03:47 AM

Calculation:	Compare
Results:	Impact assessment
Product 1:	10000 kg Rock wool, packed, at plant/CH U (of project Ecoinvent unit processes)
Product 2:	3200 kg Glass wool mat, at plant/CH U (of project Ecoinvent unit processes)
Product 3:	3500 kg Cellulose fibre, inclusive blowing in, at plant/CH U (of project Ecoinvent unit processes)
Product 4:	600 kg Urea formaldehyde foam, in situ foaming, at plant/CH U (of project Ecoinvent unit processes)
Method:	Eco-indicator 99 (H) V2.09 / Europe EI 99 H/A
Indicator:	Weighting
Unit:	kPt
Skip categories:	Never
Exclude infrastructure processes:	No
Exclude long-term emissions:	No
Per impact category:	Yes
Sorted on item:	Impact category
Sort order:	Ascending

Comparing 1E4 kg 'Rock wool, packed, at plant/CH U', 3.2E3 kg 'Glass wool mat, at plant/CH U', 3.5E3 kg 'Cellulose fibre, inclusive blowing in, at plant/CH U' and 600 kg 'Urea formaldehyde foam, in situ foaming, at plant/CH U';
Method: Eco-indicator 99 (H) V2.09 / Europe EI 99 H/A / Weighting

Figure 16. SimaPro® 7.3.3 Impact Assessment of Insulation Materials.

During the proprietary phase of this IQP we reviewed a variety of literature with respect to LCA tools and specifically focused on SimaPro®. We had concluded in our review that there are many applications SimaPro® can be used for such as: "carbon footprint calculation, product design, eco-design, and environmental product declarations" ("Thermal and Environmental Evaluation Information Guide V2," 2013). If one speaks to any professional in the field that is familiar with LCA and LCA software tools then they most likely have a working knowledge of SimaPro® or at least an opinion on the program. The clear cut advantages of SimaPro® are the wealth of databases from around the world that can be downloaded and utilized, the seemingly endless granularity when considering life cycle processes, and the ability to compare and contrast materials in the quantities that will be used during the production process. It was also very easy to upload databases to SimaPro® to regionally customize materials for all over the world depending on where the project is located. The worldwide information that SimaPro® allows access to is why the Solar Decathlon competition required the use of this software. It was beneficial to all Solar Decathlon teams to use because it will provide a fair baseline for the competition graders. Even though the Solar Decathlon competition will grade SimaPro®'s calculations, the use of other existing LCA tools was legal and will enhance a team's overall material selection process.

4.3 Existing LCA Tools

The demand for these tools was not prevalent in the construction industry and therefore it is not seen on the everyday consumer level. This was confirmed by Dr. Viola John and her colleague Ian Häfliger, who are two professionals we spoke with at ETH. We share the same opinion, in that SimaPro® was more applicable to post construction analysis. This was a major disadvantage to the program from our perspective because we were unable to use SimaPro® as a material selection tool. Given our lack of experience using life cycle assessment tools, getting to know SimaPro® entailed a steep learning curve. We took numerous tutorials to understand the complex commands required to link and compare materials together, as required by the Solar Decathlon committee. As we discussed SimaPro® with other users, they all noted how complex and expensive the software was and there was no free and easy tech support. This contributed to the lack of knowledge and resources because SimaPro® has not gain popularity yet.

After using the software to conduct several analyses presented above, we concluded that, SimaPro® has several key disadvantages for novice users, such as students in the Solar Decathlon competition. First, SimaPro® would only be beneficial if the parameters of the project were extremely large. Parameters are defined as size, complexity, quality, productivity, completion time, or cost. This entailed that the parameter of the project should be a complete cradle-to-grave analysis of the materials' life cycle. Secondly, SimaPro® required a wealth of information about each material or process in order to conduct a complete analysis. The data provided must be exact and in appropriate metric because no assumptions could be made automatically by software or the results will be incomplete and skewed. Finally, there was no direct "score" that a material or building can get based on all entered criteria. This was why comparisons between materials are more widely beneficial. They allowed for a direct comparison instead of a percentage of values in different categories that had no real base statistics.

A major component of this project was to evaluate SimaPro® as a tool. By comparing SimaPro® with other existing tools, we identified several advantages and disadvantages of the tools in various situations. HSLU made a number of reasonable assumptions and decisions regarding the materials selection, but the choice of materials did not consider sustainability as a key parameter initially. As a result, some material choices were suboptimal. An important difference in our suggested process is that students should investigate possible material selection software to aid in their material selection, seen in Table 3.

Table 3. LCA Tool Comparison.

	BEES®	Sustainable Minds	GaBi	ATHENA® Impact Estimator	ATHENA® EcoCalculator	Bauteil Katalog	SimaPro®
Free	✓	✓				✓	
Analyze all stages	✓		✓	✓	✓	✓	✓
Flexible	✓	✓	✓				
Web-based		✓				✓	
Side-by-side comparison		✓				✓	✓
Ecoinvent			✓			✓	✓
Steep Learning Curve			✓				✓
Process Tree	✓	✓	✓	✓			✓
Tutorials	✓	✓	✓	✓	✓		✓
Life of materials	✓		✓	✓	✓	✓	✓
Visual Display of environmental impact			✓			✓	
Alternative sustainable designs		✓		✓			
Whole building analysis		✓		✓	✓	✓	✓
Individual material analysis	✓					✓	✓
Operational Energy	✓			✓		✓	✓
Regionally Customized	✓			✓	✓	✓	✓

BEES® (Building for Environmental and Economic Sustainability) is primarily a material selection tool, whereas SimaPro® conducts a post analysis of the materials. Although they both measure environmental impact, BEES® can measure the overall economic performance of the material. This is beneficial because it can provide important information as to how the material could save the building owner money in the future.

ATHENA® EcoCalculator only analyzes overall sustainability of the building materials compared with other building materials. It also calculates the global warming potential from the buildings. SimaPro® indirectly covers the global warming potential.

ATHENA Impact Estimator only evaluates the final building design whether or not it is sustainable. It offers over 1,000 design options that could improve the original building envelope parameters. SimaPro® is similar in the way that it evaluates a building as a whole; however, SimaPro® does not give suggestions on how to improve the user's current project.

Sustainable Minds is similar to SimaPro® in that it allows for comparison for materials using the ecoinvent database. The program has the ability to upload materials from 3D modeling programs. Sustainable Minds is available online for free, or can be purchased, which allows for more various parameters.

GaBi and SimaPro® are two popular and time consuming programs, in that they have a steep learning curve. However, GaBi allows for flexible inputs and outputs, whereas SimaPro® needs exact data for an input value.

Dr. Viola John, an expert in LCA in the construction industry, believed SimaPro® was the best LCA tool; however it is structurally inconvenient. In other words, it is hard to navigate and difficult to learn. She had high praise for Bauteil Katalog. She remarked that it has a better level of granularity and is visually friendly, as a scaled bar display with symbolic colors of its environmental impact is displayed. Practical applications for SimaPro® are to use it as an auditing post analysis software. When selecting materials, SimaPro® was not the best software prior to material selection, especially on a large scale. When a product has been manufactured, or in this case, the prototype built, a SimaPro® LCA could yield results that support material selection. One can learn which processes have a lengthy chain behind them as well as its life's consumption of any commodity.

Ian Häfliger, the research assistant on the board of sustainable construction at ETH, works with LCA tools. He also highly recommended Bauteil Katalog as a material selection software.

He claimed Bauteil Katalog is good for quick evaluations and it gives accurate results for basic design processes. Ian would recommend that the HSLU team should use Bauteil Katalog in the beginning as a guide, because it is not good for complex analysis. SimaPro® is better at complex analysis, including recycling of the materials, which Bauteil Katalog lacks. Both pieces of software use ecoinvent for their database. SimaPro® has the option of exporting information to a Microsoft Excel® spreadsheet. Bauteil Katalog does not have that option, but requires the user to copy and paste information from the website to a different format, which can result in errors.

It is easier to use Bauteil Katalog in order to receive values for gaps HSLU has currently with SimaPro®. Bauteil Katalog also outputs building analysis, such as the effects a building currently has and how it should be improved. By using the Bauteil Katalog, users would not have to guess if the material would be sustainable or not; they can see how it will impact the house before they order the material. In practice, SimaPro® is too complicated and cannot provide the option of material selection, whereas Bauteil Katalog offers an array of material combinations. Therefore, there are many other LCA tools that can be utilized alongside SimaPro® for future HSLU teams.

5. Conclusions and Recommendations

Based on our findings, we developed a number of conclusions and recommendations that future Solar Decathlon teams at HSLU may use to streamline decision making process so they can more efficiently and effectively meet the competition deadlines while ensuring a high quality product that meets the competition criteria. We created a recommended process of material selection that utilizes a number of tools available to students which is shown in Figures 17 and 18. The suggested process is divided into three phases: Design, Construction, and Review. We assessed how life cycle assessment tools in general and SimaPro® in particular can be used in the Solar Decathlon competition specifically but also their roles more broadly in construction industry in the future. We believe utilizing our recommendations would greatly benefit future Solar Decathlon teams and ensure that they effectively communicate, manage time, and select sustainable materials in the best possible way so that they can succeed in the competition. We present our conclusions and recommendations in three subsections below regarding first the team decision making process in general, followed by the materials selection process in particular. We wrap up the discussion with some conclusions and recommendations regarding life cycle analysis tools, including SimaPro.

The HSLU team did a fantastic job in developing an innovative approach based on promoting sustainability through an urban design that emphasizes shared space as a way to save on materials and energy use. The approach challenges one of the fundamental emphases of the Solar Decathlon competition on the sustainability of the materials used in construction and energy generation and consumption during use. Our research focused on the team's decision making regarding materials choices. Given the HSLU team's emphasis on the design of shared space, it comes to no surprise that materials choice was given less emphasis. Thus, some of our conclusions may appear a little harsh, since our focus was on their decision making regarding materials choices. The conclusions and recommendations are intended as constructive criticism to enable future HSLU Solar Decathlon teams to compete even more effectively. It is from this perspective that we wish the 2014 HSLU Solar Decathlon team good luck in the competition in Versailles, France.

5.1 Team Composition and Decision Making

Conclusion 1.1: There are numerous advantages to having an interdisciplinary team of students with diverse backgrounds and practical experience. One of the major strengths of the HSLU Solar Decathlon team was that half of the students were graduate students who had taken advanced courses that helped them with their assigned tasks for the design and construction of the prototype house. The team included students with a variety of backgrounds in architecture and different aspects of engineering (such as electrical, mechanical, and so forth). This interdisciplinary background was beneficial because each student contributed different perspectives about what features were important and how to build the house. Furthermore, some of the students had several years as apprentices in various trades, therefore they knew what materials were commonly used and had contacts that could help the team. These students were able to assist enormously with the practical aspects of the competition, not just theoretical, because this was not their first time working on a construction project. This contrasts to WPI's 2013 Solar Decathlon team in which no student had industry experience.

Recommendation 1.1: We recommend that in future a Solar Decathlon team should be recruited to include a broad mix of students with diverse interdisciplinary, theoretical, and practical skills.

Conclusion 1.2: The Sustainability Report was an important requirement of the competition, but a major hurdle for the HSLU team due to limited English reading and writing skills within the team. We found that a major problem in the approach to the Sustainability Report (which was an important requirement of the competition) was that the main student writing it was not a native English speaker. As a result, the report was unclear, very difficult to follow, and required substantial editing prior to submission. Although Randy Cotten, who is originally from America and a native English speaker, reviewed the document for its clarity, he was unable to give it his full attention due to the competing demands on his time and the multiple project deadlines.

Recommendation 1.2: We recommend that in future the student or students selected to prepare the Sustainability Report and other required documentation for the competition

should be carefully selected to have appropriate skills in reading and writing English. Also, their other responsibilities to the project should be limited to ensure they can pay full attention document preparation.

Conclusion 1.3: The HSLU team did not establish decision making rules or procedures for resolving disputes in advance; rather their decision making process developed in a relatively ad hoc fashion. Every Thursday, the HSLU team came together and discussed what they completed and were still working on to inform the rest of the team. These weekly meetings were beneficial as they ensured that those who were present at the meetings were informed about what others completed and additional tasks were outstanding. From speaking with the HSLU team, communication on the materials selection process could be improved in future teams. At team meetings when ideas for materials were presented, materials were not voted upon. Instead, the discussion was prolonged as people expressed their opinions on materials and the team lost time in their meetings due to much debate. The choice of the flooring was pressured because the team could not agree on what to use. Eventually the student leader, Marcel, made the final call on material decisions. It put the HSLU team behind in the process and the time they spent in their group meetings debating the flooring, they felt could have been better spent doing other tasks. The HSLU team did not manage their time effectively and worked to the last minute to finish competition deliverables.

Recommendation 1.3: Any future HSLU Solar Decathlon team should take the time at the beginning of the process to establish clear responsibilities and ground rules for decision making and resolving disputes.

5.2 Conclusions Regarding the Material Selection Process

Conclusion 2.1: Given their emphasis on the design of shared space as a concept, the HSLU team did not identify materials selection as a key criterion initially. Even though the sustainability of materials was a key part of the Solar Decathlon competition, the HSLU team used other criteria initially for their selection of design, components, and materials. For example, the architectural team chose bathroom and kitchen tiles based on texture as opposed to focusing on the sustainability of the materials. The only advantage of these tiles was that they were made of recycled items such as plastic and gravel. Similarly, the HVAC team chose the most efficient system and did not focus on the environmental impact of each individual material within the system.

Recommendation 2.1: We recommend that any future HSLU Solar Decathlon team explicitly recognize the need to choose materials carefully based on measures of their sustainability.

Conclusion 2.2: Scenario analysis using SimaPro revealed that some of the materials choices made by the team were less than optimal in terms of sustainability, although these choices can be justified on various grounds. Using SimaPro, we discovered that poured concrete would be a more sustainable option over wood and steel for the foundation of the y**our**$^+$ house and that urea formaldehyde foam and cellulose fiber were better options in terms of environmental impact than the rock wool. The HSLU team chose wood and steel for the prototype to enable it to be shipped to Versailles. Once the prototype was built at HSLU, it was disassembled to transport it to the competition. Therefore, using poured concrete for the foundation would not have been a viable option. In addition, rock wool was chosen because of local availability and cost. However, if they were to have chosen urea formaldehyde foam and cellulose fiber, that would have been the more sustainable option which was concluded using SimaPro.

Recommendation 2.2.1: We recommend that the current HSLU team use the data from our analysis and SimaPro to explain to the Solar Decathlon judges that they recognize the limitations of their materials selection for the prototype.

Recommendation 2.2.2: We recommend that the HSLU team explain to the Solar Decathlon judges that additional materials analysis using SimaPro and/or other LCA tools will be used to identify more sustainable materials for use in the full-scale concept building for which the your+ house is a precursor.

Recommendation 2.2.3: We recommend that future HSLU teams use SimaPro or other LCA tools to help choose and justify materials selection choices.

Conclusion 2.3: The HSLU team decision making process for materials selection was relatively ad hoc as a result of their early emphasis on the concepts of shared space and only later consideration of materials selection as required by the Solar Decathlon competition. The HSLU team did incomplete research into the sustainability of potential materials. For example, the architects limited potential materials based on the visual appeal and turned to the materials' manufacturers for information on the materials 'sustainability. Based on the information they gained, they chose materials; there was no additional research completed on materials.

Conclusion 2.4: The organization of the master list was less than optimal due to the belated focus on materials selection. The Solar Decathlon competition requires teams submit a detailed list of materials used in their house with information on the materials, including their transport and end-of-life. The HSLU students had many students log data into a Microsoft Excel™ sheet. As a result, there were many versions of the document with different materials information on each. When our team approached the compilation of the materials list, we had to chase down all students involved in the materials list to obtain everyone's material information. This process was tedious and time consuming. In addition, the compilation of the materials list was done during the end of the construction process. It would have been more efficient to compile the information as materials were chosen and ordered.

Conclusion 2.5: The HSLU team utilized the contractor Renggli late in the Construction Phase. Students on the HSLU team recognized working with the contractor earlier in the Design Phase would result in a more efficient Construction Phase because they could review the building designs sooner and provide their expert opinion.

Recommendation 2.3: To address Conclusions 2.3, 2.4, and 2.5, we recommend the next HSLU Solar Decathlon team adopt the following Material Selection Process that we believe is more effective (Figure 17 and 18). It is divided into three phases: Design, Construction, and Review.

Design Phase

In the Design Phase, the HSLU team should take into consideration researching common materials versus sustainable materials. Instead of choosing materials based on visual appeal and the material's texture, we recommend the materials should be picked based on sustainability. To do this, the team should research and select a proper material selection software that best fits their needs. There are many existing LCA tools that aid in selection of sustainable materials such as Bauteil Katalog. The LCA values of the materials will add up once the house is built, and it is more efficient to pick sustainable materials from the beginning to have a better chance of winning the Solar Decathlon competition. When that is done, they should bring in the contractor earlier in the design phase and get them involved with their design processes as a consultant.

After the appropriate tool is selected, materials would then be inputted and decisions on materials would be adjusted based upon software feedback. The purpose of the software is to choose the best sustainable material for the user's specific project. It would inform the team how each material is made and whether the process of recycling is truly sustainable. A desirable software would give a value for each material and the software would display side-by-side comparisons. This would help accelerate material selection process. Once the materials have been selected, they would be approved by the team. Lastly, the design of the house and the selected materials would be sent to the contractor. We recommend the HSLU team should get in contact with the manufacture of the materials and perform research properties of the material such as how much greenhouse emissions were released when producing the material, how well it insulates, and its durability. In the Recommended Process, specifically in the Design Phase, the contractor should be brought on early as a consultant. This would allow the team to have more knowledge early on regarding the materials and their construction. By having more steps in the Design Phase, it will save time during the Construction phase.

Construction Phase

In the Construction Phase of our recommended process, the contractor should order materials to begin the construction of the house. As soon as the materials arrive for construction, the materials' LCA data should be inputted into the Solar Decathlon Excel Sheet. This would organize the team's materials and values for the purpose of referring back to them and sending it to the Solar Decathlon Committee.

Review Phase

The Review Phase consists of completing construction on the house and conducting a post-analysis. The LCA data on the Solar Decathlon Excel sheet would be inputted into SimaPro®, a software required by the Solar Decathlon competition. The team would use the outputs from SimaPro® as a mean to justify choices made with the use of the material selection software. From this, they would create comparison graphs that show the advantages or disadvantages of the selected materials. This would be submitted to the Solar Decathlon committee along with their house for the competition.

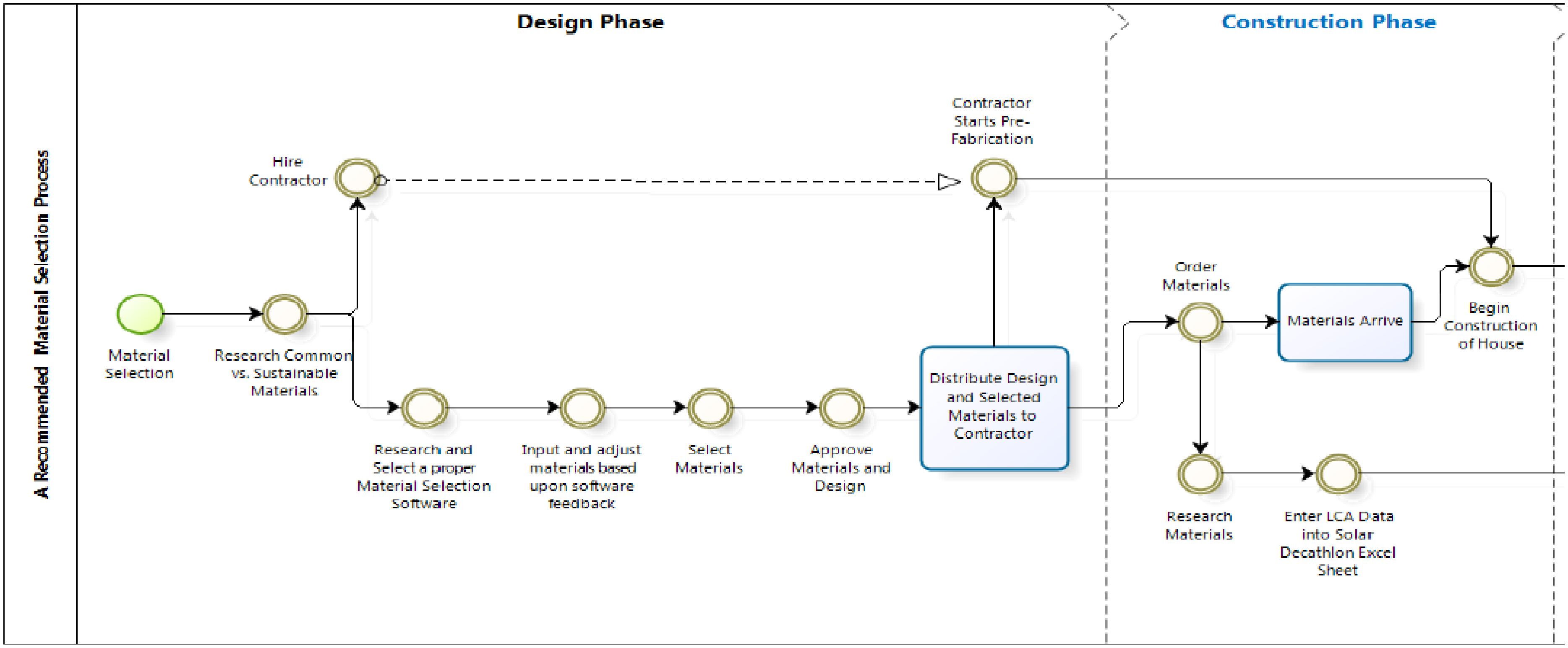


Figure 17. A Recommended Material Selection Process Part 1.

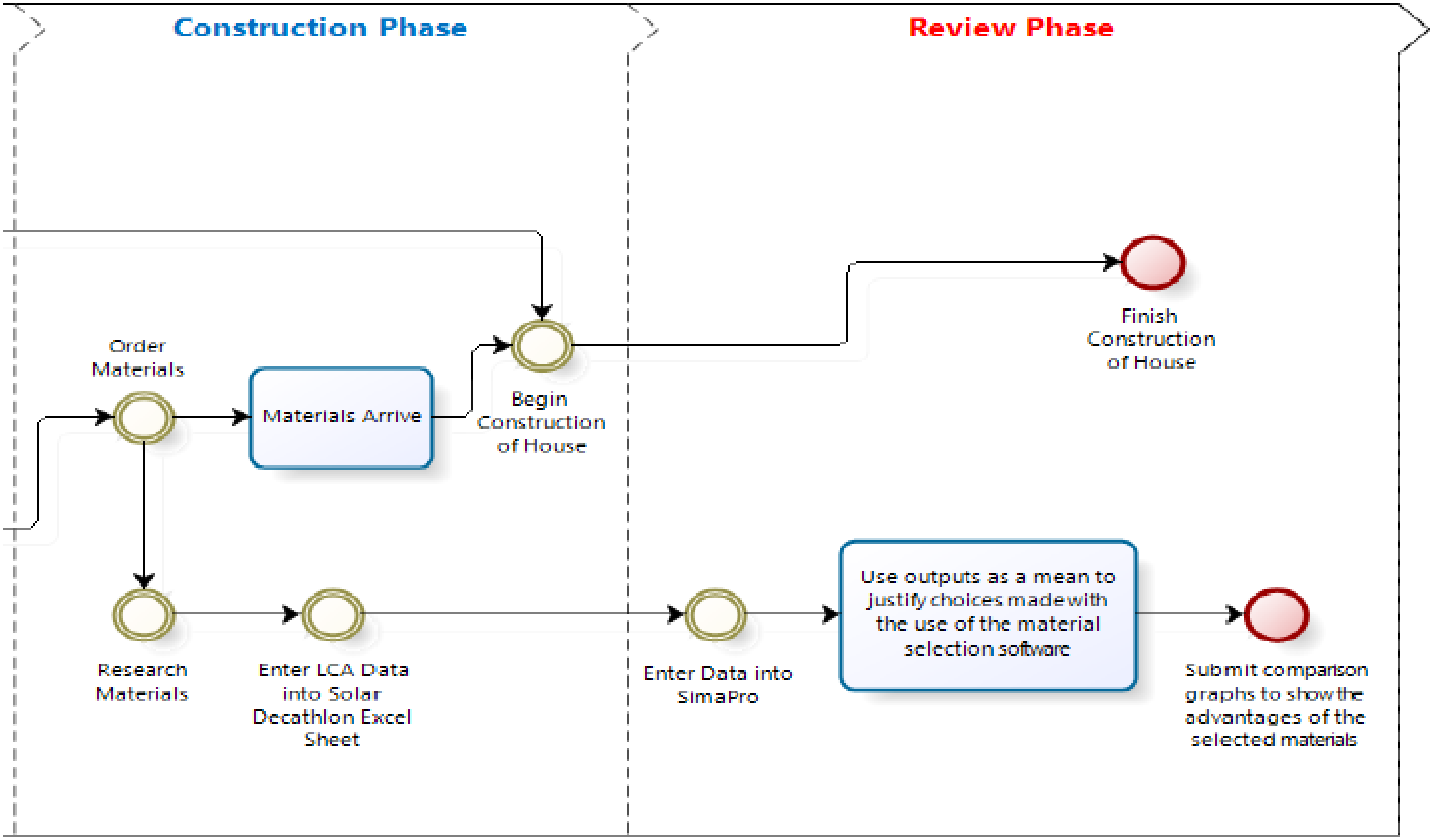


Figure 18. A Recommended Material Selection Process Part 2.

5.3 Conclusions Regarding Life Cycle Assessment

The driving force behind innovation is competition between companies. Construction companies are constantly looking for new ways to better their opponents. Recently, Life Cycle Assessment (LCA) has been the only acceptable analysis. SimaPro® has been in the forefront of the LCA software industry. SimaPro® takes into account every aspect of cradle-to-grave analysis. Using SimaPro® you can include processes from the harvesting of the material to the reuse and eventually the final disposal. The Solar Decathlon competition required the use of SimaPro® to display the materials' sustainability and environmental impact.

Conclusion 3.1: SimaPro® has a steep learning curve and takes considerable time and effort to master. The complexity of the software did not allow the HSLU team to benefit from the in depth comparisons and analysis that can be produced. This software has a seemingly endless amount of granularity that causes users to become overwhelmed with data entry. Even with the tutorials that are provided on their website, this program still requires ample time to learn basic functions.

Recommendation 3.1.1: Future HSLU teams should use the SimaPro® Guide we developed and designate one person per disciplinary group to learn SimaPro®.

Recommendation 3.1.2: SimaPro® needs to simplify its user interface and improve its support network.

Conclusion 3.2: SimaPro® provides enormous analytical power which may not be necessary or desirable for initial materials selection, but can be extremely useful for checking, justifying, and demonstrating decisions after the fact. Our group concluded, with the given guidelines from the Solar Decathlon competition, that SimaPro® is best used as a justification tool. SimaPro® uses the ecoinvent database to compare and evaluate the materials life cycle perfectly. If the parameters of the project are well defined, SimaPro® will incorporate all aspects of the defined scope.

The final result of data analysis that SimaPro® produces is in the form of a graph, table or chart. Comparisons can be produced between materials that are options for a certain attribute of a structure. Also, the software produces visuals, such as pie charts and impact assessments, for individual materials. These charts and impact assessments will show the impact that any given material has on the environment through a number of indicators such as, climate change, carcinogens, and fossil fuel production. This diversity of the software enables SimaPro® to compare materials in a visual form but also allows a display of an individual material. The processes with the highest environmental impacts are highlighted so that the user/designer is aware of the sustainability of each process. The visual comparisons are the best utilized product of SimaPro®. These comparisons work well because processes such as transportation are included as high impacts on the environmental sustainability. Individual components for transportation, such as ethanol or other basic materials, are organized and accessible to show total environmental impact.

Recommendation 3.2: We recommend that future HSLU teams use more simple LCA tools, such as Bauteil Katalog, or hand calculations to assess material sustainability. SimaPro can be used to provide more in-depth analysis of selected materials decisions to justify choices made.

Conclusion 3.3: When constructing a sustainable building, life cycle assessment methods in conjunction with the ecoinvent database is the best practice. In spite of the accuracy of SimaPro®'s ecoinvent database, it is not utilized by industries to its fullest potential in all countries. Ecoinvent is the most popular database regarding material information in the world. This popularity has been obtained by providing many sources of input data for all regions of the world. This database is the standard for LCA software and there is no doubt that it should be. It covers all of the necessary information regarding material information. When users look to document their materials in a software they search for a database that covers their geographical location, materials, and processes the best. The future of its application falls into two categories. First is a LCA software like SimaPro®. Second is a modeling software such as AutoCAD® or SolidWorks®. A modeling software is one that an architect or engineer uses when designing a product. These software are highly sought after by architects in the field and as of right now they are the most common way to use ecoinvent.

Recommendation 3.3.1: We recommend that rising architects and engineers familiarize themselves with the practices of LCA and databases like ecoinvent.

Recommendation 3.3.2: The construction industry should head towards using software programs that incorporate ecoinvent, like SimaPro®.

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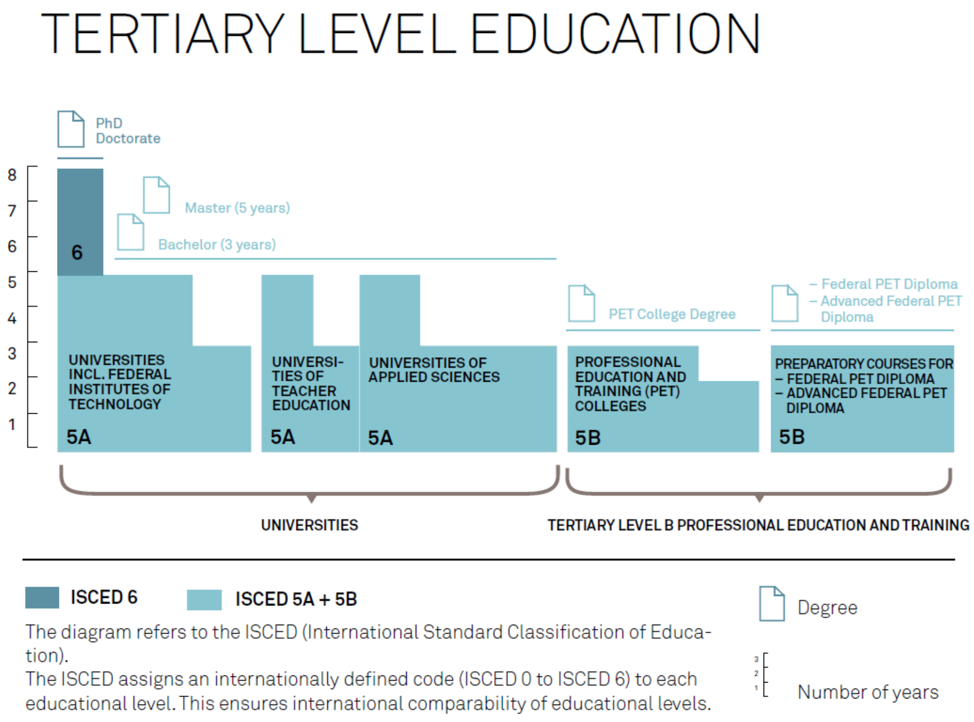
Appendix A: Sponsor Description

Tertiary education in Switzerland is similar to a college education in the United States. There are two types of tertiary education in Switzerland: level A and level B. Level A is comprised of cantonal universities and Federal Institutes of Technology, universities of applied sciences, and universities of teacher education. For admittance into a tertiary Level A institution, a baccalaureate or a Federal Vocational Baccalaureate is required. Level B is for people who have completed vocational training and education and would like to enhance their skills. It offers Federal PET (Professional Education and Training) Diploma Examinations and Advances Federal PET Diploma Examinations and PET colleges ("Tertiary Education," 2013). Figure 1 illustrates the different sections of tertiary education. There are 10 cantonal universities and two Federal Institutes of Technology ("Swiss Education," 2013). Figure 2 shows the amount of students by discipline in the universities in 2012.



The diagram refers to the ISCED (International Standard Classification of Education).
The ISCED assigns an internationally defined code (ISCED 0 to ISCED 6) to each educational level. This ensures international comparability of educational levels.

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Figure 1. Tertiary Level Education Overview ("Tertiary Education," 2013).

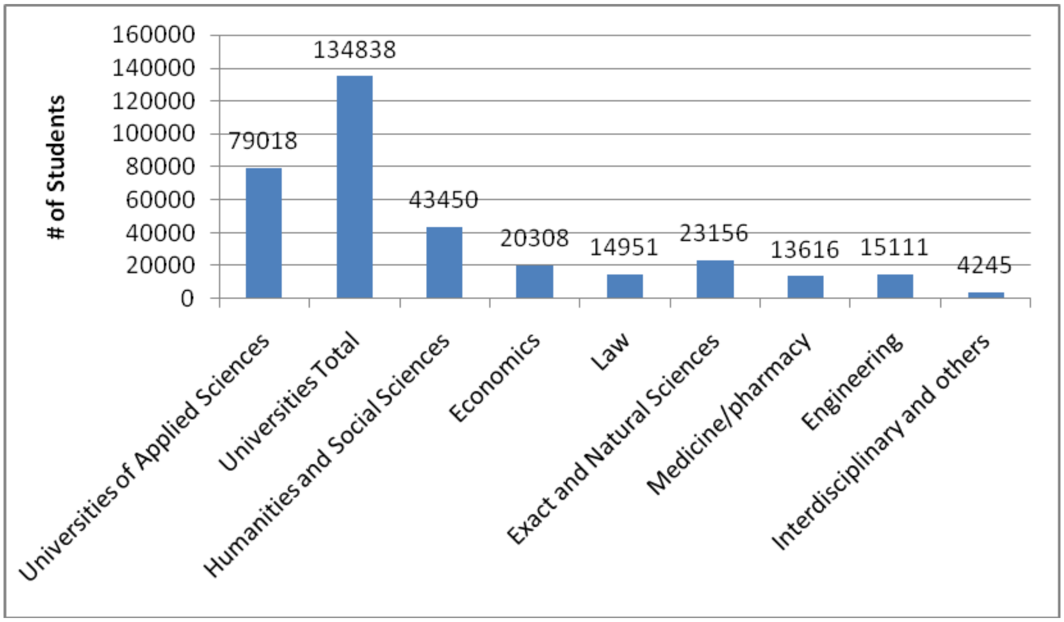


Figure 2. Breakdown of Students at Universities("Education Statistics 2012," 2013).

One type of tertiary Level A institution is the university of applied sciences. Created in the 1990’s, these universities are the result of the merge of PET colleges. They offer more hands-on degree programs that set students up to become professionals in their field by offering both bachelor and master degrees. They admit students who have a Federal Vocational Baccalaureate. There are seven public universities of applied sciences in Switzerland ("Swiss Education," 2013).

One of these universities is HSLU. It offers education in the following schools: Engineering and Architecture, Business, Social Work, Art and Design, and Music. Today, it is a public university that has contracts with many partner schools and actively promotes student research all over the globe.

HSLU was established in 1997 from merger of several older technical schools into the current five schools at the university. The School of Business was merged from many smaller schools, including HöhereWirtschafts und Verwaltungsschule (HWV, School of Higher Education in Business and Administration), established in 1971; InstitutfürBetriebs und Regionalökonomie (IBR, Institute for Management and Regional Economics), also established in 1971; the School of Business Information Technology and the Lucerne School of Tourism, established in the 1980s; and the Institute of Financial Services, established in the 1990s. The smaller schools were merged together in 1997. The School of Art and Design was originally established as an art school in 1783 and changed to its current title in 1997. The School of Social Work and School of Music were also merged into the school in 1997.

Switzerland was transformed by industrialism which made it necessary in 1899 to create high educational institutions in technology. However World War I and II held back the plans and it was not until 1946 that the Central Swiss Engineering Night School was formed. Finally after years of preparation, the ZentralschweizerischesTechnikum Luzern (ZTL) also known as the Lucerne Central Swiss School of Technology was created in 1958. At first the school offered only two classes, one in Electrical Engineering and the other in Mechanical Engineering. In 1959 the Civil Engineering Department was created followed by the Heating, Ventilation and Air-Conditioning Department in 1960 (“History of the School of Engineering and Architecture”, 2014).

Eventually the school outgrew its original facilities and construction on a new campus began in 1972. By 1977 the Central Swiss Engineering Night School and ZTL had fully moved to the new location. In 1997 the School of Engineering and Architecture was formed by reorganizing ZTL and the Evening Technological School of Central Switzerland together. The School of Engineering and Architecture became part of the University of Applied Sciences and Arts. In 1999, the former Lucerne Central Swiss School of Technology and the Central Swiss Engineering Night School officially merged together into the School of Engineering and Architecture that is around today and became offering more courses along with research and development. The degree programs were reformed to offer both bachelor and master degrees in 2005 (“History of the School of Engineering and Architecture”, 2014). Currently, there are 8 bachelor programs and 2 master programs available for students in the School of Engineering and Architecture. The five schools made up the University of Applied Sciences of Central Switzerland, and in 2007 the name was changed to the current name. (“Hochschule Luzern”, 2014). As of the end of the 2012, academic year, the Lucerne University of Applied Sciences and Arts had a total of 5,515 students in degree earning programs as seen in Figure 3 (“Aktuellezahlen und fakten”, 2012).

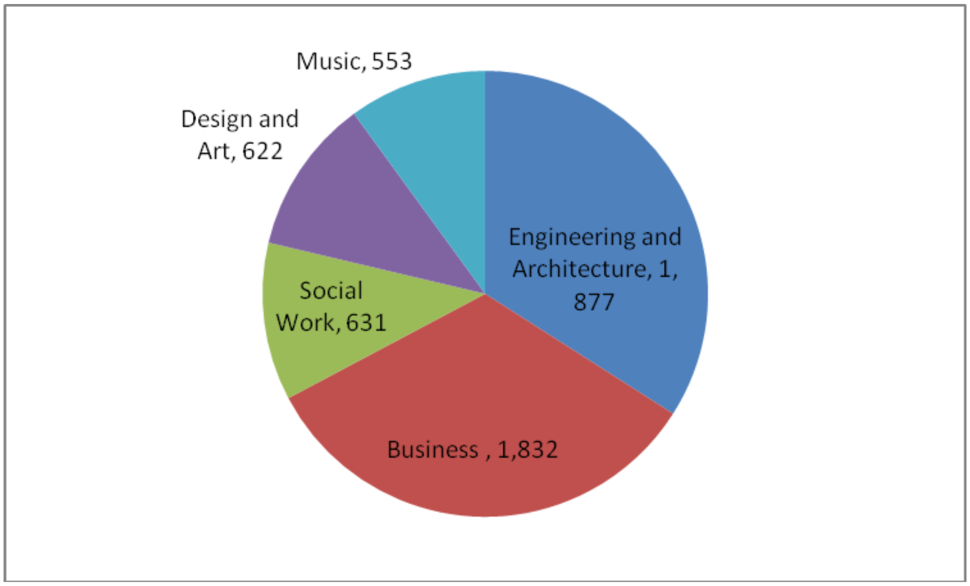


Figure 3. Number of Bachelor and Master Degree Students in each Schoolin 2012 ("Aktuellezahlen und fakten", 2012).

Several groups oversee the governance and administration of the university. The Konkordatsrat is the highest authority at the university and is composed of one member from the government in each of the six central Swiss cantons that the university serves primarily. The University Council, comprising eight representatives from industry and academia, is in charge of strategic leadership. The Rector, who is equivalent to a university president in the United States, is responsible for organizational management. Together, the Rector, heads of each of the five schools, the Executive Director, and the Head of Marketing and Communications form the University Management ("Lucerne University of Applied Sciences and Arts").

The School of Engineering and Architecture is geared towards research, teaching, and training. Although studies were interrupted due to World War I, The Great Depression, and World War II, it persevered to maintain its mission ("History of the School of Engineering and Architecture"). It works closely with industry as well as the other four schools at the university. Research at the school focuses on the transition to more sustainable uses of energy and building design and construction as holistic and integrated systems, whether it is solar energy or interior design ("Application-Oriented Research for the Building as a System and the Energy Transition"). There are multiple institutes at the university that work on both building design and energy transition.

Seven categories of research at the School of Engineering and Architecture include: Architecture, Civil and Structural Engineering, Building Technology, Electrical Engineering, Information and Communications Technology, Mechanical Engineering, and Business Engineering/Innovation. The Building Technology projects utilize the Integrated Building Technology Center, a very new and top of the line facility for research. Using this facility as well as the outside Swiss Research Center for Building Intelligence (CEESAR), the Lucerne University of Applied Sciences and Arts is able to attract many sponsors and students to work with them. A focus of the Architecture Department is Envelopes and Solar Energy while the Structural Department is developing Façade and Metal engineering. Integrated, Intelligent, and Efficient Energy Systems is another in a long list of advanced research projects that are available to students.

Professor Schulz is the Program Director of the Business Engineering and Sustainable Energy Systems Program which is a bachelor's degree program at the School of Engineering and Architecture ("Research and Development"). Starting in 2012, the program's goal is to educate business engineering students interested in entering an energy related industry ("Bachelor in Business Engineering Sustainable Energy Systems"). The program starts off with interdisciplinary project groups that work together to solve general tasks in the field of engineering and business. During the latter part of their studies, students work on more sophisticated problems and end with a final thesis in a specific field of sustainable energy systems to finish their Bachelor's degree.

Extensive knowledge in engineering laboratories is emphasized by Professor Schulz and his colleagues in order to promote hands on learning in their degree requirements. Some of these are materials, electricity, thermodynamics, and fluid dynamics laboratories. As mentioned above, they also emphasize creating well-rounded students. Therefore courses in non-technical fields are required, such as classes within the University Schools of Business, Social Work, and Art & Design. Professor Schulz, along with Professor Shaun West, will oversee the EcoBalance project.

The EcoBalance project, sponsored by HSLU, is an interdisciplinary project which involves evaluating and making recommendations of web-based tutorials on lifecycle analysis to optimize construction design. It includes social as well as environmental applications, to determine how the Swiss approach sustainability with reference to the United States. Since the university is passionate about hands on learning, it is important to recommend an easy-to-use, informative guide to display how to use the SimaPro®.

Appendix B: Interview Script

The appendix below contains preambles that we will use while conducting interviews with people outside of HSLU while in Switzerland. These interviews will be with various people that work in sustainable construction organizations to help us understand their approach and documentation process in choosing sustainable materials for buildings.

Swiss Preamble

Our names are [team members present] and we are a student project team from the United States conducting research in cooperation with Hochschule Lucerne. They are participating in the Solar Decathlon competition this summer for the first time where they are developing a conceptual model of a sustainable house. We are looking at their documentation and decision making process behind the materials selection for their house design. This will allow us to create a proposed procedure for future sustainable construction projects. This interview will help us further our research and give us insight in what others in this field are doing.

We would like you to know that this interview is voluntary and that you may stop the interview at any point or refuse to answer any of the questions we ask. We will be taking notes during this interview and will record it if it is alright with you. Is it alright if we use your name and title in our final published product? If so, how would you like to be identified? We can send you the product before it is finalized if you would like to review it.

General Questions

1. What is your background/expertise at [the company they work at]?
2. What is your position and main responsibilities?
3. How educated are you on LCA?
4. What areas of LCA are you concentrating on?
5. How important is LCA in choosing materials?
6. What methods do you and others at your company use to choose materials for sustainable buildings?
7. Do you use any software, tools, or databases to help decide what materials to use?
    a. If yes:

        i. How is that software, tool, or database helpful?
        ii. What made you and others decide to use it?
        iii. Have you found any drawbacks in its ease of use?
        iv. If you were making a guide to give tips and hints on how to use it, how would you make it?

8. How do you document the decision making process?
9. Are there any methods you used in the past to document your decision making process that did not work?
10. Are there any aspects of your decision making process that you think works really well?
11. Do you have any suggestions of people within your organization that we could contact to get more information?
12. Can we contact you again if we have further questions?
13. We greatly appreciate you taking time out of your day to answer our questions. They have been very useful to us.

Appendix C: Focus Group

We are going to conduct a focus group with students on HSLU's Solar Decathlon team. Below is our proposed script for the focus group. The questions and the order we ask them may change once we arrive in Switzerland.

Script:

Preamble: Our names are [names of team members present] and we are a student project team from a university in the United States conducting research in cooperation with HSLU. We are looking at your decision making and documentation process in materials selection for your Solar Decathlon house design as well as creating a guide for using SimaPro®. This focus group will help us understand how you approached the project and propose a procedure for future teams to use. Do you mind if we record this discussion? Although we will be taking notes of your responses, we will keep your responses anonymous.

Discussion Topics for HSLU Team:

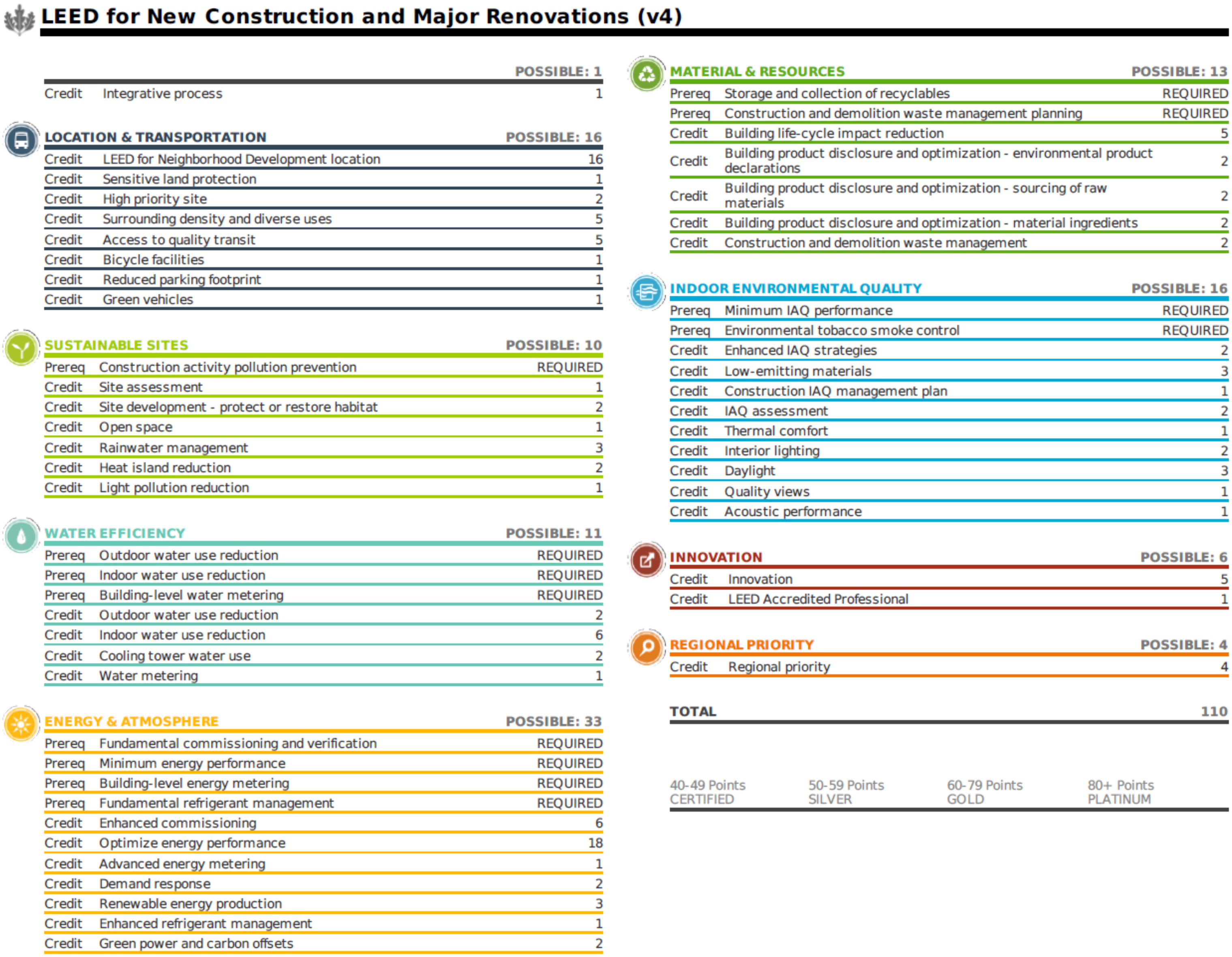
- How do you decide what materials to use for your prototype house design?
- How do you document your decision making process for material selection?
- What part of the project did you focus on the most because it was the most difficult?
- Is there anything about your current materials selection process that you think can be improved?
- Is there anything about your current materials selection process that you think works well for the team?
- How do you organize and communicate with each other regarding materials?
- Do you have any suggestions on how the materials selection process can be improved for future teams to use?
- Where are you in the materials selection process right now?
    - What do you have left to pick materials for?

Questions for Randy Cotten:

- Why is no one else on the team using SimaPro®?

- Was anyone else interested in learning how to use it? Why/why not?
- Did anyone else try to learn how to use SimaPro® or was it you right from the beginning?
- How do you relay information learned on SimaPro® to your team?
- How do you document what you learn from SimaPro®?
- How useful is what you take away/learn from SimaPro® for the project?
- What do you like about SimaPro®?
- What do you not like about SimaPro®?
- Is there anything that you found particularly difficult to do on SimaPro® that you would like to be improved?
- Do you think having a group of people on the team whose focus is using SimaPro® would be helpful?
- Is there anything else you would like to talk about regarding SimaPro®?

Appendix D: LEED Rating for New Construction and Major Renovation



LEED for New Construction and Major Renovations (v4)

		POSSIBLE: 1
Credit	Integrative process	1

LOCATION & TRANSPORTATION		POSSIBLE: 16
Credit	LEED for Neighborhood Development location	16
Credit	Sensitive land protection	1
Credit	High priority site	2
Credit	Surrounding density and diverse uses	5
Credit	Access to quality transit	5
Credit	Bicycle facilities	1
Credit	Reduced parking footprint	1
Credit	Green vehicles	1

SUSTAINABLE SITES		POSSIBLE: 10
Prereq	Construction activity pollution prevention	REQUIRED
Credit	Site assessment	1
Credit	Site development - protect or restore habitat	2
Credit	Open space	1
Credit	Rainwater management	3
Credit	Heat island reduction	2
Credit	Light pollution reduction	1

WATER EFFICIENCY		POSSIBLE: 11
Prereq	Outdoor water use reduction	REQUIRED
Prereq	Indoor water use reduction	REQUIRED
Prereq	Building-level water metering	REQUIRED
Credit	Outdoor water use reduction	2
Credit	Indoor water use reduction	6
Credit	Cooling tower water use	2
Credit	Water metering	1

ENERGY & ATMOSPHERE		POSSIBLE: 33
Prereq	Fundamental commissioning and verification	REQUIRED
Prereq	Minimum energy performance	REQUIRED
Prereq	Building-level energy metering	REQUIRED
Prereq	Fundamental refrigerant management	REQUIRED
Credit	Enhanced commissioning	6
Credit	Optimize energy performance	18
Credit	Advanced energy metering	1
Credit	Demand response	2
Credit	Renewable energy production	3
Credit	Enhanced refrigerant management	1
Credit	Green power and carbon offsets	2

MATERIAL & RESOURCES		POSSIBLE: 13
Prereq	Storage and collection of recyclables	REQUIRED
Prereq	Construction and demolition waste management planning	REQUIRED
Credit	Building life-cycle impact reduction	5
Credit	Building product disclosure and optimization - environmental product declarations	2
Credit	Building product disclosure and optimization - sourcing of raw materials	2
Credit	Building product disclosure and optimization - material ingredients	2
Credit	Construction and demolition waste management	2

INDOOR ENVIRONMENTAL QUALITY		POSSIBLE: 16
Prereq	Minimum IAQ performance	REQUIRED
Prereq	Environmental tobacco smoke control	REQUIRED
Credit	Enhanced IAQ strategies	2
Credit	Low-emitting materials	3
Credit	Construction IAQ management plan	1
Credit	IAQ assessment	2
Credit	Thermal comfort	1
Credit	Interior lighting	2
Credit	Daylight	3
Credit	Quality views	1
Credit	Acoustic performance	1

INNOVATION		POSSIBLE: 6
Credit	Innovation	5
Credit	LEED Accredited Professional	1

REGIONAL PRIORITY		POSSIBLE: 4
Credit	Regional priority	4

TOTAL	110

40-49 Points	50-59 Points	60-79 Points	80+ Points
CERTIFIED	SILVER	GOLD	PLATINUM

Appendix E: LEED

USGBC's *Green building and LEED core concepts guide (2009)*, list Assessments and Measurements (see below). These benchmarks for measurement are simplified criteria that are used to quickly assess a sustainable design effort.

- **Rapidly renewable materials.** The amount of a building's agricultural products (fiber or animal) that are quickly grown or raised and can be harvested in a sustainable fashion, expressed as a percentage of the total materials cost. For LEED, rapidly renewable materials take 10 years or less to grow or raise.
- **Recycled content.** The percentage of material in a product that is recycled from the manufacturing waste stream (pre-consumer waste) or the consumer waste stream (postconsumer waste) and used to make new materials. For LEED, recycled content is typically expressed as a percentage of the total material volume or weight.
- **Regional materials.** The amount of a building's materials that are extracted, processed, and manufactured close to a project site, expressed as a percentage of the total materials cost. For LEED, regional materials originate within 805 kilometers of the project site.
- **Reuse.** The amount of building materials returned to active use (in the same or a related capacity as their original use), expressed as a percentage of the total materials cost of a building. The salvaged materials are incorporated into the new building, thereby extending the lifetime of materials that would otherwise be discarded.
- **Sustainable forestry.** The practice of managing forest resources to meet the long-term forest product needs of humans while maintaining the biodiversity of forested landscapes.
- **Waste division.** The amount of waste disposed other than through incineration or in landfills, expressed in tons. Examples of waste diversion include reuse and recycling.

Waste Management methods are crucial as a part of the construction process and also assessed as part of LEED requirements. The solid waste generated in a project is transported to landfills or sometimes incinerated to generate energy. As of 2009, the U.S. recycled 32% of its solid waste, increasing this to 35% would save more than 5 million metric tons of carbon dioxide equivalent (*Green building*, 2009).

Part of life cycle impact is made when purchasing construction materials. To aid in sustainable purchasing the USGBC recommends developers:

- **Develop a construction purchasing policy.** Outline the goals, thresholds, and procedures for procurement of construction materials. Monitor compliance and track the effectiveness of the policy to ensure that it is working.
- **Specify green materials.** Rapidly renewable materials, regional materials, salvaged materials, and materials with recycled content reduce environmental impacts and promote sustainable material sources.

- **Specify green interiors.** Use finishes, carpets, fabric, and other materials with low levels of volatile organic compounds (VOCs), formaldehyde, and other potentially toxic chemicals to protect indoor environmental quality and reduce life-cycle impacts of materials.

(*Green building*, 2009)

Appendix F: Focus Group Notes

Focus Group #1

While conducting the focus group with students on the HSLU solar decathlon team, a member of our group took notes as shown below.

March 27th, 2014

Attendance: Randy Cotten, Fiona Berger, Roger Hauswirth, Azi Azizi, Lauren Tice, Tim Love, Wil Michalski

Location: Around a table outside of the Solar Decathlon team office

Fiona Berger (interior design student):

- Works for architectural department as teaching assistant and full time on project
- Received bachelor's degree in the summer of 2013
- Worked on Interior Design portion of *my room*, *your room*, *our room* and *space+*
- Material Selection process for the wall material was chosen by her and one other person.
- Different colors for each room was picked in order to distinguish between rooms
- Materials that could have been used on the walls for wallpaper are:
    - Cotton
    - Fiberglass
    - Linen
- Wall paper was chosen because it is flexible and prevents the walls from breaking during transport to Versailles, France
- Wall paper was recommended by the architectural/building engineers who specialize in module houses
- Not many dangerous components in wall paper
- Fiberglass wallpaper was chosen because:
    - Recommended by manufacturer.
    - More durable and will last better during transport of the house to France.
    - Reacts with light better than other material choices

    - Is not a harmful material to human skin/lungs/eyes etc.
    - Did not look into the sustainability of fiberglass material beyond knowing its lifespan

Floor Material

- Renggli (Construction Company) wood engineers that pick wood for construction. Your+ team took their word and went with their material selection.
- Smoked oak from France was picked based off of look, feel and composite 3 layer thin design
- Lots of discussions on which wood to use within the whole team at the weekly Thursday meetings
- Oak was picked because:
    - Thin composition
    - Not a luxury home therefore the wood does not need to be expensive
    - Ran out of time for discussions and a decision needed to be made

Heating, Cooling, Ventilation and Sanitary Systems (HVAC)

Roger Hauswirth: building engineer bachelor student in 4th year

- Materials for this section were chosen by 4 different people on the HVAC team
- Looked mainly at technical requirements needed for each system
- To design HVAC sustainably, this is different than the architectural choices because the working procedure is more important
- They had space limits, electrical requirements, and heating and cooling requirements
- The HVAC system should run efficiently and air flow uses the least amount of energy as possible
- The materials that comprise the ducts, boiler, or the whole unit, they do not care about
- Used local companies and manufacturers to reduce import costs and trucking emissions

- Did not worry about choosing the “best” materials because the industry standard is very high
- Less concern about the materials that go into the system, more concern/thought about if the system works efficiently
- There was one person who specialized in either cooling, heating, ventilation, or sanitary systems

Ceiling:

- Aluminum ceiling was picked even though it does not look attractive
    - It was chosen because of its cooling capacity
- Chose materials for the ceiling based off of requirements given by the architects

Water Collection, polyethylene insulation:

- Ducts and pipes are mainly stainless steel because they run under the bottom floor where they are exposed to elements and sometimes are not protected

In General:

- The quantity of materials was a factor in materials selection because if less of a more unsustainable material is used, that’s okay with them
- Fiona and one other person chose materials for the wall and floors
- There was no intercommunication on materials between them and the other groups except on the choice for the floor
- In the weekly meeting, everyone sat around a table and expressed their opinions on a material for the floor, no voting occurred
    - Finally chose the material when the team realized they needed to move on and not waste anymore time discussing
- The team ordered much more material for foundation than needed and will ship it back to the company, better to have more and run out than to not receive enough.
- Both Fiona and Roger believed that if Renggli had been involved from the beginning it would have made things go smoother

  - They theoretically designed first without materials, then as time went on they made material choices
  - Then Renggli was on board and began helping and was a consultant on materials they use and have used before. Sometimes they know more and are experienced
- Students generally are familiar with the materials and manufacturers before starting on the Solar Decathlon project because many of them worked for various companies in the past before coming to school
- Stayed away from plastics and other synthetic materials
- Used mostly local materials
- Discussions about materials were stressful so decisions were eventually made
- There was a list where everyone was supposed to write down their materials but they did not know where it was and people stopped writing on it

Focus Group #2

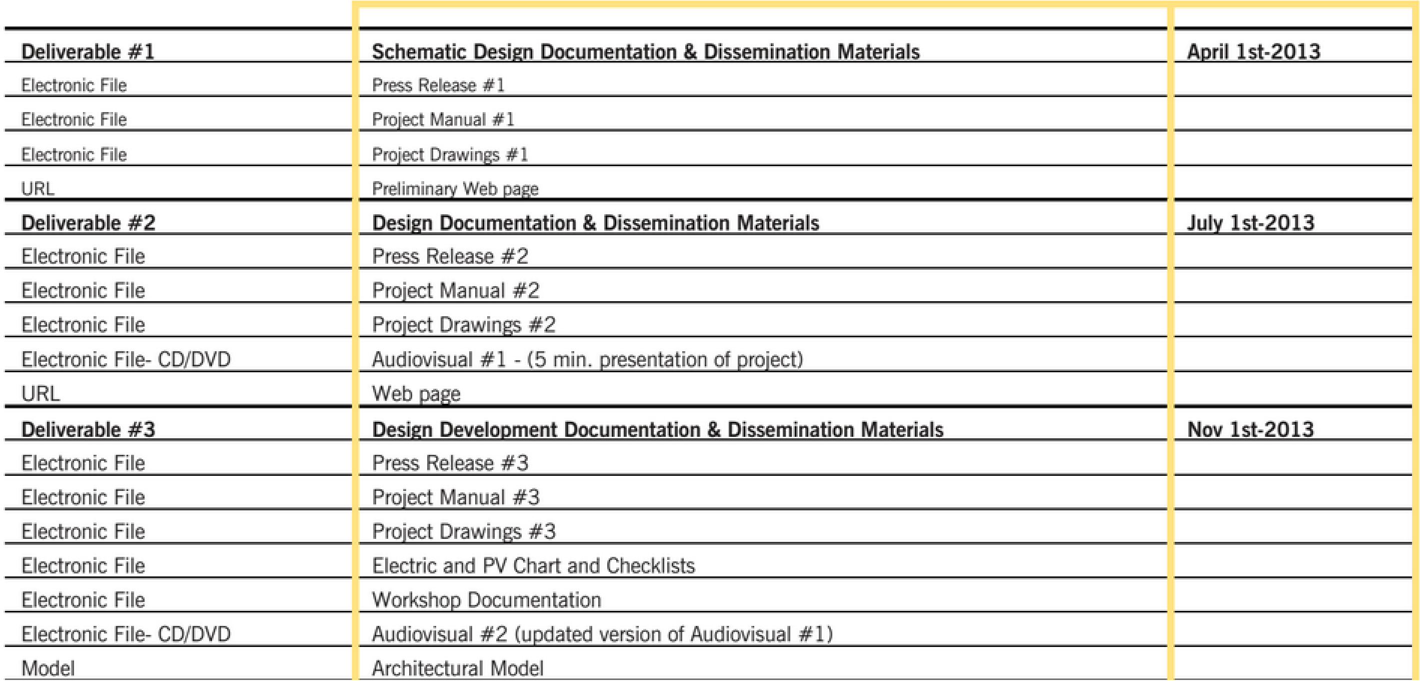
April 25th, 2014
Attendance: Daniel Arnold, Roger Hauswirth, Patrick Uccellis, Janick Staub, Samuel Bieri, Wil Michalski
Location: Around a picnic table at lunch

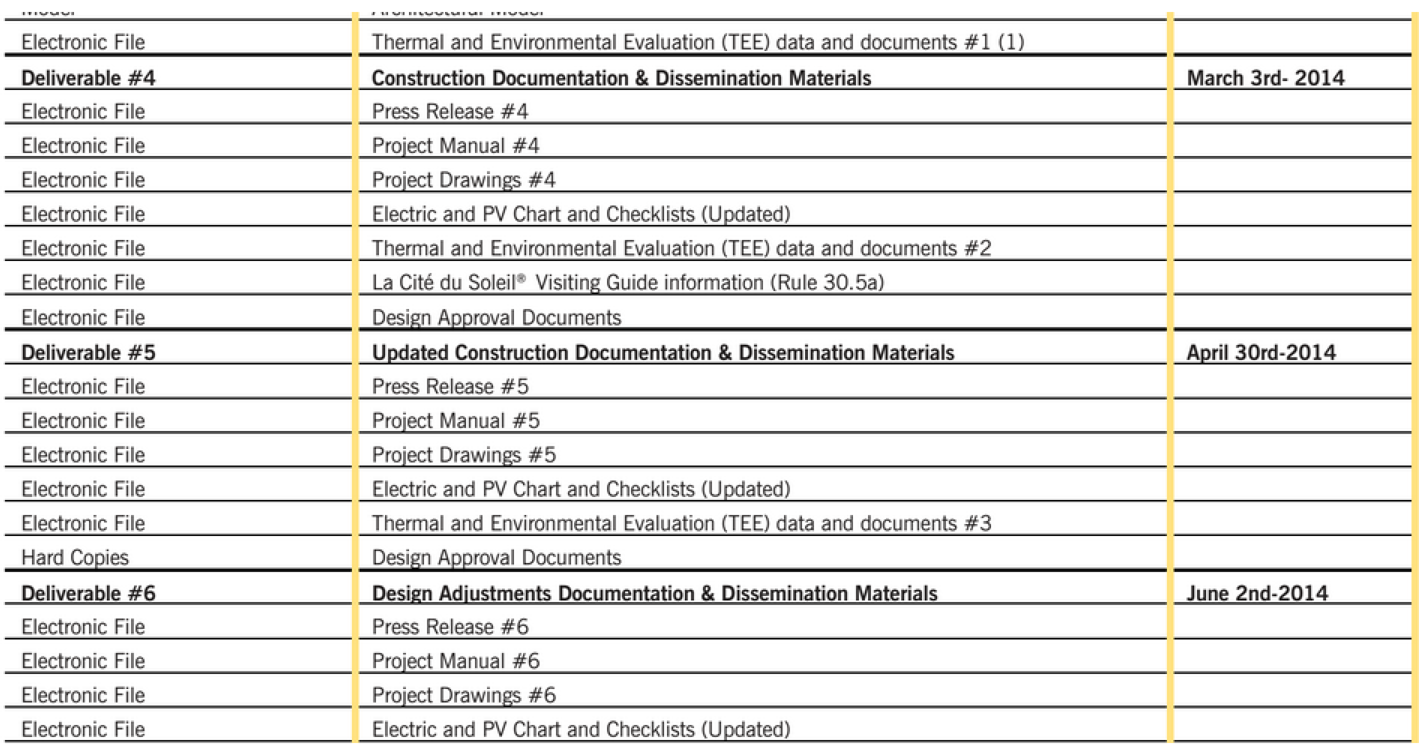
Patrick Uccellis: Team Coordinator for Electrical Engineering, grad student
JanickStaub: Communications, undergrad, studying Business Engineering
Samuel Bieri: Integration of Electric Mobility, undergrad, studying Electrical Engineering
Daniel Arnold:
-Bachelor of Architecture, graduate student
-Health and Safety Team Coordinator
Responsibilities:
- To assure that all workers are well pre-paired and trained to work on all construction.
- To ensure that every work step and all instruments needed are as safe as possible.
- To check that all laws and rules concerning health and safety are followed.
-He organizing courses
- He checks the certifications of sub-contractors
- He writes the H & S Plan and draws the H & S drawings

- Around 50% of the team are graduate students
- Most team members had to apply, some were asked by professors
- Professors were team leaders at the beginning then after a reorganization, student leaders who had emerged were appointed
- Around 70 students total, 30-40 working every day at one point or another
- 10 professionals on the job site
- Specialized groups of the team are: Architects, building engineers (HVACS, electrical), Information Technology (IT), Interior Design, Design & Art, Business Engineering, and Electrical Engineering

- Of these groups, one member of each volunteered to be a part of the Communications group which helps in coordination between all groups.
- As part of the rules, there is a 5 kW peak energy output of the solar panels
- They chose the most efficient panels after researching the best then found a local company that sold them.
- The architects built from the inside out to ensure a proper building footprint.
- Shared Space required coordination and sacrifices as the architects wanted increased sunlight in the Space Plus but the HVAC team wanted less light to keep temperatures down.
- Rain/Grey/Fresh Water
    - Most Swiss appliances have rain water adapters so the SD 2014 Committee made an exception for HSLU.
    - In accordance to rules, they are using grey water for irrigation
    - They are using grey water for the recooling device as well which was not in the rules, but instead an applied technology.
    - Rain water will be used for the first cycles of a washer machine's process to soak clothes, then fresh water used for the actual cleaning cycles.
    - The sink is connected to the toilet, water used to rinse hands will be pumped into the toilet reservoir as flushing water
    - Hot water from the shower will heat copper coils under the shower floor which in turn help heat the fresh water from the shower head.
- There are required water, electric, and heat meters that the Committee requires be installed for their measuring devices.
- It will require 10 trucks, maximum 40ton per truck to transport the house
- Marcel runs Thursday meetings and keeps track of due dates and deliverables
- Architects work +60 hours a week
- Some team members volunteer to perform extra work despite not being acknowledged or remembered. There is a genuine passion for success.

Appendix G: Solar Decathlon 2014 Deliverable Deadlines





Deliverable #1	**Schematic Design Documentation & Dissemination Materials**	**April 1st-2013**
Electronic File	Press Release #1	
Electronic File	Project Manual #1	
Electronic File	Project Drawings #1	
URL	Preliminary Web page	
Deliverable #2	**Design Documentation & Dissemination Materials**	**July 1st-2013**
Electronic File	Press Release #2	
Electronic File	Project Manual #2	
Electronic File	Project Drawings #2	
Electronic File- CD/DVD	Audiovisual #1 - (5 min. presentation of project)	
URL	Web page	
Deliverable #3	**Design Development Documentation & Dissemination Materials**	**Nov 1st-2013**
Electronic File	Press Release #3	
Electronic File	Project Manual #3	
Electronic File	Project Drawings #3	
Electronic File	Electric and PV Chart and Checklists	
Electronic File	Workshop Documentation	
Electronic File- CD/DVD	Audiovisual #2 (updated version of Audiovisual #1)	
Model	Architectural Model	
Electronic File	Thermal and Environmental Evaluation (TEE) data and documents #1 (1)	
Deliverable #4	**Construction Documentation & Dissemination Materials**	**March 3rd- 2014**
Electronic File	Press Release #4	
Electronic File	Project Manual #4	
Electronic File	Project Drawings #4	
Electronic File	Electric and PV Chart and Checklists (Updated)	
Electronic File	Thermal and Environmental Evaluation (TEE) data and documents #2	
Electronic File	La Cité du Soleil® Visiting Guide information (Rule 30.5a)	
Electronic File	Design Approval Documents	
Deliverable #5	**Updated Construction Documentation & Dissemination Materials**	**April 30rd-2014**
Electronic File	Press Release #5	
Electronic File	Project Manual #5	
Electronic File	Project Drawings #5	
Electronic File	Electric and PV Chart and Checklists (Updated)	
Electronic File	Thermal and Environmental Evaluation (TEE) data and documents #3	
Hard Copies	Design Approval Documents	
Deliverable #6	**Design Adjustments Documentation & Dissemination Materials**	**June 2nd-2014**
Electronic File	Press Release #6	
Electronic File	Project Manual #6	
Electronic File	Project Drawings #6	
Electronic File	Electric and PV Chart and Checklists (Updated)	

Electronic File	Jury Reports (Rule 30.5b)	
Electronic File- CD/DVD	Audiovisual #3 - (5 min. presentation of final project)	
Hard Copies	Design Approval Documents	
Deliverable #7	**As Built Documentation & Dissemination Materials**	**Nov 3rd-2014**
Electronic File	Press Release #7	
Electronic File	Project Manual #7	
Electronic File	Project Drawings #7	
Electronic File	Electric and PV Chart and Checklists	
Electronic File	SDE 2014 Official Dissemination Materials	
Electronic File	Thermal and Environmental Evaluation (TEE) data and documents #4 (Recap)	

(1) Thermal and Environmental Evaluation (TEE) data and documents #1 must be submitted on November 29th, 2013.

Appendix H: Glossary of Abbreviations

AP – Accredited Professional
BMCC – Building material and component combinations
BSI – British Standard Institute
BTU – British Thermal Unit
CEESAR - Swiss Research Center for Building Intelligence
CO_2 - Carbon Dioxide
CSI – Construction Specifications Institute
GBCI – Green Building Certification Institute
HSLU – Hochschule Lucerne or Lucerne University of Applied Sciences and Arts
HWV - School of Higher Education in Business and Administration
IBR - Institute for Management and Regional Economics
ILCD – International reference Life Cycle Data system
ISO - International Organization of Standardization
LCA - Life Cycle Assessment
LCCA – Life Cycle Cost Analysis
LCEA – Life Cycle Energy Analysis
LCI – Life Cycle Inventory Analysis
LCIA – Life Cycle Impact Assessment
LEED – Leadership in Energy and Environmental Design
PET – Professional Education and Training
REPA – Resource and Environmental Profile Analysis
SF – Square-foot
US DoE – US Department of Energy
USEPA – US Environmental Protection Agency
USGBC – United States Green Building Council
VOC – Volatile Organic Compound
WPC – Whole process of the construction
WPI – Worcester Polytechnic Institute
ZTL – Zentralschweizerisches Technikum Luzern