전과정 평가기법을 통한 복합재 차체의 환경영향 예측
The Estimation for Environmental Impact of Composite Bodyshell Using Life Cycle Assessment (LCA)

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ABSTRACT

본 연구는 차체재질로 복합재 적용한 경우를 기존의 금속구조 차체와 25년 운행기간을 기준으로 환경영향을 비교평가하였다. 본 연구는 알루미늄, 스틸, 하이브리드 복합재, 전체 복합재 인 총 4종의 차체를 고려하였다. 네가지 차체 시나리오에 대해 원자재 생산, 차체 제작, 25년 사용 단계, 폐기까지의 환경영향에 대해 LCA 기법을 사용하여 평가하였다. 모든 시나리오 경우, 사용단계가 환경영향 카테고리를 좌우했다. 전체 복합재 시나리오가 매립 또는 소각에 대한 가장 낮은 영향을 주었다. 복합재 차체는 금속차체와 비교해 환경영향 측면에서 30~50 % 개선효과를 보였다.

1. Introduction

Life Cycle Assessment (LCA) is a decision support tool for quantifying products or services based on resource uses and emission burdens. LCA is helpful for priorities identification, for pollution prevention and for reducing the consumption of resources and ultimately leads to products with the potential, and advantages of an improved life-cycle performance. An LCA accounts for the emissions and the consumptions of resources at every stage in a product's life cycle, from its cradle to its grave (raw material extraction, energy acquisition, manufacturing, use, and waste disposal), to calculate indicators of the likelihood (risks) and consequences of associated impacts. Practitioners consider indicators for climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological effects, the depletion of resources, water consumption, land use, etc. The framework for applicability of Life Cycle Assessment (Fig. 1) has been initially defined in the ISO 14040 and series[1] and is based on :

1) The Scope and Goal definition : definition of a system linked to the product to analyse,
2) The Life Cycle Inventory : inventory of the inputs and the outputs of this system,
3) The Life Cycle Impact Assessment : assessment of potential environmental impacts linked to these inputs and outputs,
4) The interpretation of the results of the inventory and the environmental assessment based on the objectives of the study.

As shown in Fig. 2, LCI results with similar impact pathways (e.g. all elementary flows influencing stratospheric ozone concentrations) are grouped into impact categories at midpoint level, also called midpoint categories. A midpoint indicator characterizes the elementary flows and other environmental interventions that contribute to the same impact. The term 'midpoint' expresses the fact that this point is located somewhere on an intermediate position between the LCI results and the damage (or endpoint) on the impact pathway. In consequence, a further step may allocate these midpoint categories to one or more damage categories, the latter representing quality changes of the environment.

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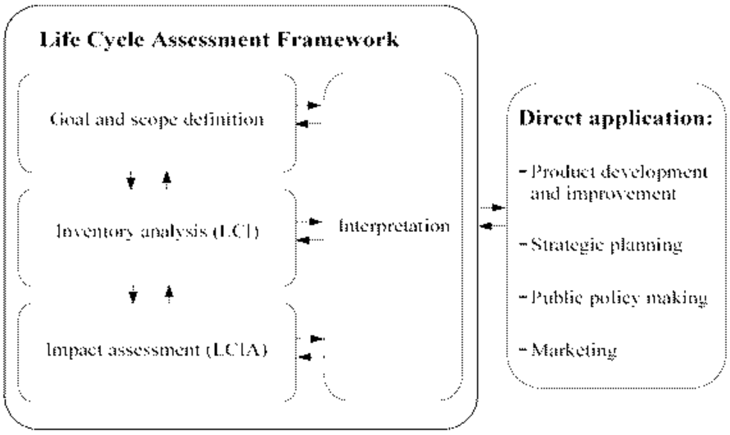

Fig. 1 Phases of Life Cycle Assessment

A damage indicator result is the quantified representation of this quality change. In practice, a damage indicator result is always a simplified model of a complex reality, giving only a coarse approximation to the quality status of the item.

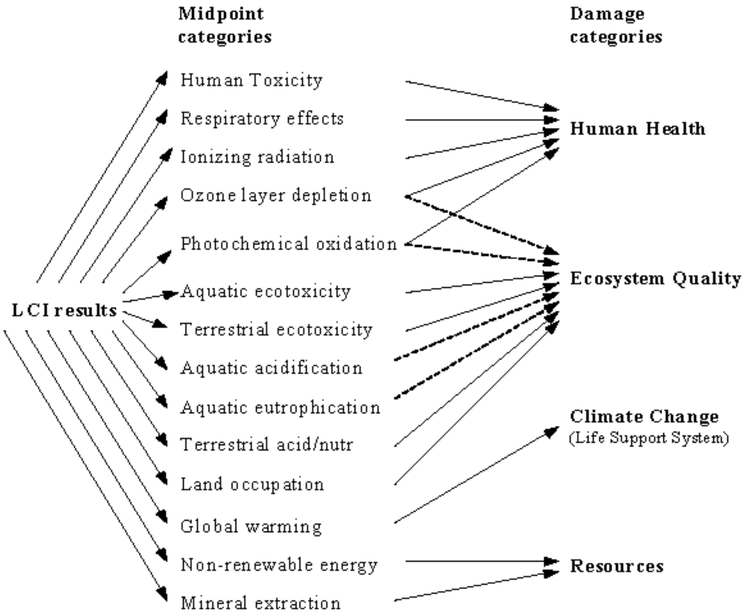

Fig. 2 Overall scheme of LCI results via midpoint/damage categories

2. Data source

2.1 Data source

The raw materials extraction, material transformation and energy are taken from Ecoinvent Database, a state-of-the-art European database developed by the Swiss Centre for Life Cycle Inventories, which contains more than 2500 processes[2]. Data for the production of carbon fiber are taken from IDEMAT Database (developed at the Delft University of technology, the Netherlands). The inputs for the model are the material composition of the car-bodies, defined following Hankuk Fibers[3].

2.2 Scenario details and quality of the data

This LCA study compares four car-body scenarios :

1) Scenario 1: Full composite car-body, with a carbon fibers epoxy aluminium honeycomb sandwich structure and a stainless steel under-frame
2) Scenario 2: Hybrid composite car-body, with a carbon fibers epoxy aluminium honeycomb sandwich structure, a mild steel inner-frame and a stainless steel under-frame
3) Scenario 3: Aluminium car-body, with a 100% aluminium structure
4) Scenario 4: Stainless steel car-body, with a 100% stainless steel structure

Table 1 Carbody Scenarios

	Scenario 1: **Full Composite car-body** [7.6 ton]	Scenario 2: **Hybrid composite car-body** [8.8 ton]	Scenario 3: **Steel car-body** [11.5 ton]	Scenario 4: **Aluminum car-body** [9.0 ton]
Under-frame	Stainless steel : 5.3 ton	Stainless steel : 5.3 ton	Stainless steel : 4.2 ton	None
Body Frame	Composite: 2.08 ton - 0.38 ton aluminum honeycomb - 1.7 ton CFRP 1.0 ton carbon fiber + 0.7 ton epoxy resin Bondex : 0.22 ton	Composite : 1.78 ton - 0.38 ton aluminum honeycomb - 1.4 ton CFRP 0.84 ton carbon fiber + 0.56 ton epoxy resin Bondex : 0.22 ton	Stainless Steel : 7.3 tones	Aluminum : 9 tones
Inner-frame	None	Stainless steel 1.5 tones	None	None

For each scenario, there are two end of life alternatives.

2.3 Key assumptions and related choices

Two studies have been performed: the life cycle analysis for all car-body scenarios using European electricity production and the same life cycle analysis but using Korean electricity production. Korean electricity inventory has been provided by KELA(Korea Environmental Labelling Association). Another detailed study was necessary in order to assess the energy consumption of the TTX train during its use phase.

2.4 System Boundary

The system boundaries include all the processes necessary to perform the system function. All the processes for the raw material extraction, manufacturing and use of the car body are taken into account, excluding infrastructure demand and maintenance because they are assumed to be the same for all the scenarios (see Fig. 3).

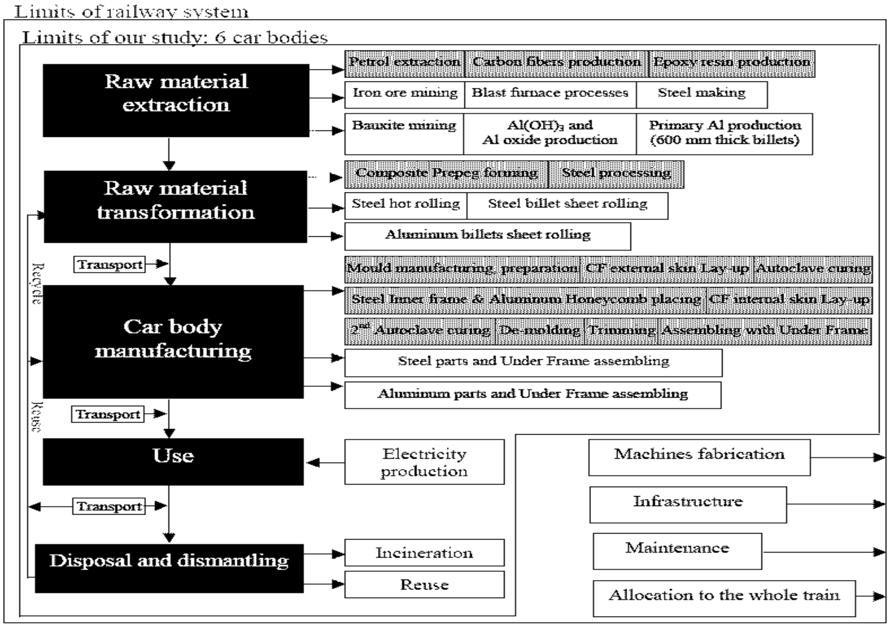

Fig. 3 System Boundaries

3. Results

3.1 Life Cycle Inventory

They have been performed using SIMAPRO software. Four scenarios have been assessed(see Table 1 "Car-body scenarios composition") and two alternatives end of life scenario have been considered for the 4 base scenarios (Table 3.4 "End of life alternatives for composite and hybrid car-bodies"). The Korean and European cases are identical in terms of assumptions and data. They differ however in the definition of their electricity mix which has been found as the most relevant key parameter between the two studies. The Korean mix based on European technology is now designated as the Korean case. The European mix based on European technology is designated as the European case.

3.1.1 Primary Energy

For all scenarios, the use phase is the most important phase in terms of primary energy consumption. However, the production phase is not negligible (see Fig. 4). End of life phase is negligible in the primary energy consumption inventory. Full Composite scenarios (both land filling and incineration end of life), appear to be the less energy demanding, with 1.91E7 MJ-eq. Hybrid Composite scenarios (both land filling and incineration) primary energy consumption is 16% higher. Concerning aluminium end of life scenarios, recycling emissions are 18% and 20% higher than for reuse. Finally, stainless steel emissions (both recycling and reuse end of life) are 46% higher.

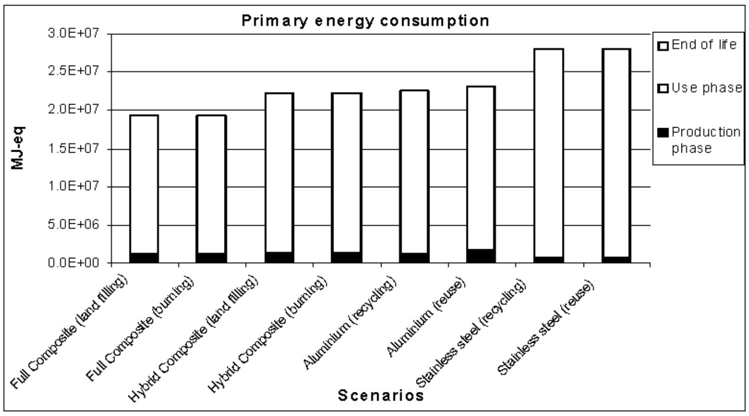

Fig. 4 Primary energy consumption over the whole life cycle for all scenarios

3.1.2 Fossil Carbon dioxide (CO_2)

For all scenarios, the emissions of carbon dioxide (fossil) are more important in the use phase. They are mainly due to the electricity consumption, which is directly linked to the weight of the car-body. The life cycle of one "full composite" car-body(both land filling and reuse scenarios for end of life) is responsible of the production of 7.8E5 kg of CO_2. Hybrid composite emissions (both land filling and incineration end of life scenarios) are 16% higher, aluminium scenario(recycling end of life) emissions are 21% bigger, aluminium scenario(reuse end of life) emissions are 24% higher and stainless steel scenarios(both recycling and reuse end of life) emissions are 48% higher. Fig. 5 represents the amount of CO_2emissions due to the life cycle for the eight scenarios.

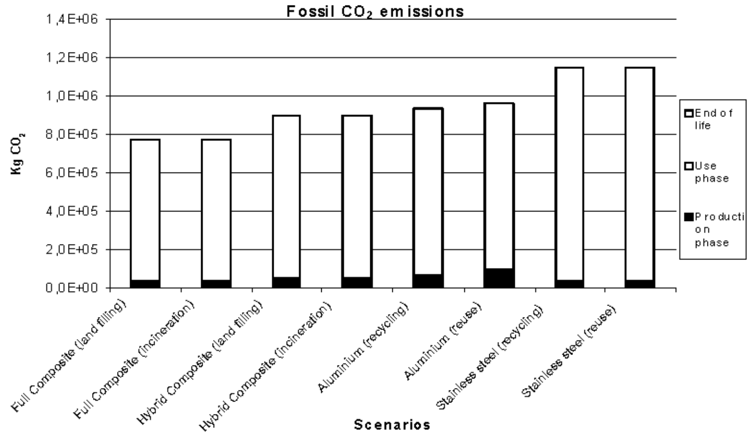

Fig. 5 CO2 emissions for all the life cycle, for all the scenarios

3.1.3 Sulphur dioxide (SO_2)

The emissions of sulphur dioxide come from the use phase. Use phase emissions are weight dependant. So, "full composite" scenarios(both land filling and incineration end of life scenario) appear to be the scenario with the lowest SO_2 emissions. Fig. 6 shows the importance of the SO_2 emissions in each life cycle step and for each scenario.

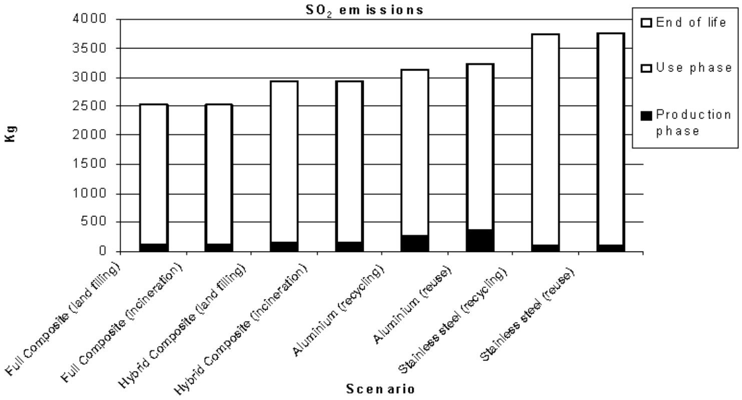

Fig. 6 SO2 emissions for all the life cycle, for all the scenarios

3.1.4 Nitrogen oxides

The use phase dominates NO_x emissions over a car-body life cycle, although the production phase is not negligible. Production phase emissions are similar for all the scenarios. End of life has no relative importance. Full composite car-bodies(both land filling and incineration end of life scenarios) appear to be the scenarios with the lowest NO_x emissions(because of its lower weight). NO_x emissions for the whole life cycle for all scenarios can be observed in Fig. 7.

3.2 Life Cycle Impact Assessment

Life cycle impact assessment(LCIA) aims to examine the product system from an environmental perspective using impact categories and category indicators connected with the LCI results.

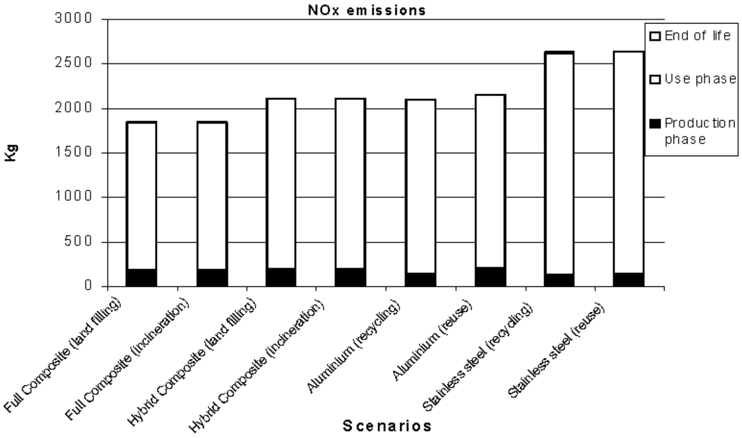

Fig. 7 NOx emissions for all the life cycle, for all the scenarios

3.2.1 Normalised damage categories results analysis

Fig. 8 shows the normalised damage categories for the full life cycle, which include all the mid-point categories weighted. They are normalised to the global effect on human health, ecosystem quality, climate change and resources over the European population. This normalisation step is question to a subjective reference and should be taken with great care. For all damage categories, it can be seen that the stainless steel car-bodies (both for recycling and reuse end of life scenarios) appear to be the scenarios with the highest impact (except aquatic acidification and eutrophication that are not normalised). For all the scenarios and for all damage categories, the use phase has the highest impact. However, the production phase is also of relative importance. End of life options (land filling, incineration, recycling and reuse) have no significant effect on the car-body Life cycle assessment.

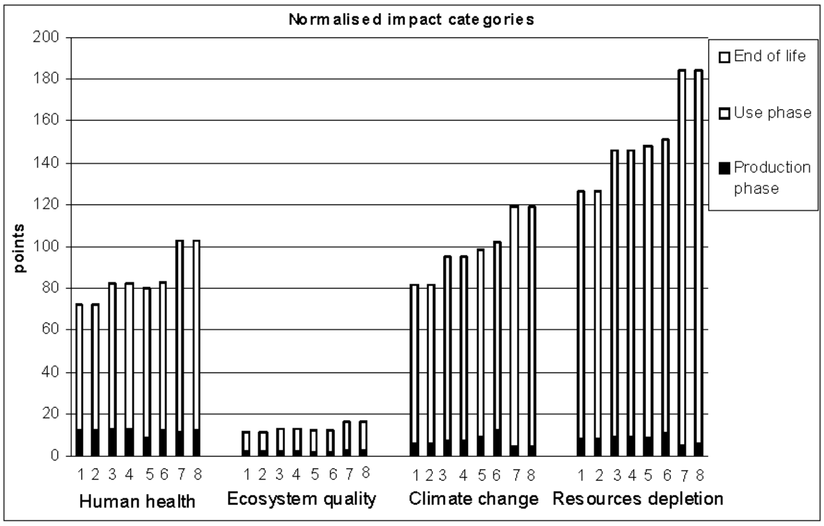

Fig. 8 Normalised Impact 2002+ damage categories for the full life cycle scenarios:

1. Korean electricity mix, Full Composite scenario (land filling)
2. Korean electricity mix, Full Composite scenario (incineration)
3. Korean electricity mix, Hybrid Composite scenario (land filling)
4. Korean electricity mix, Hybrid Composite scenario (incineration)
5. Korean electricity mix, Aluminium scenario (recycling)
6. Korean electricity mix, Aluminium scenario (reuse)
7. Korean electricity mix, Stainless steel scenario (recycling)
8. Korean electricity mix, Stainless steel scenario (reuse)

3.2.2 Life Cycle Impact Assessment : Summary

The key impact results for this LCA study are reduced to a final summary in Fig. 9. Two extreme scenarios are compared: the steel scenario and the full composite scenario, which are both assessed for the Korean and European electricity mix. Steel scenarios (3 and 4) are in all situations the most polluting, with a reduction of 30 to 50% for the full composite scenarios. These results hence strengthen the case for implementation of the composite options for the car-body in terms of environmental criteria. European cases have lower impacts than Korean cases except for human health impact. This is largely explained by the fact that the highest fraction of Korean electricity is produced via coal-fired plants. For all scenarios, the use phase is the most important phase in terms of all impacts (more than 80%). However, the production phase is not negligible and could represent 5 to 20%. End of life phase is negligible in all configurations except for a minor fraction considering the aluminium recycling within the aluminium car-body scenario. Weight is a key factor to consider when aiming at reducing the energy consumption for the use phase: a car-body weight increase of one ton implies an increase for the energy demand of 0.0259 kWh/km for this specific regional train. Considering this energy issue over the use phase, **the composite scenarios do represent a good design option**. Full composite scenarios (both landfill and incineration end of life scenarios) are identified to be the scenarios with lower impact in all midpoint categories except for terrestrial ecotoxicity where aluminium recycling is in favour of the hybrid composite scenario. Comparing European and Korean cases show that Korean electricity mix implies a higher primary energy demand (12 % for the hybrid composite scenario) and along with it a higher CO_2 and NO_x emission. SO_2 emissions are lower for the Korean case due to a lower fraction of lignite in the Korean mix.

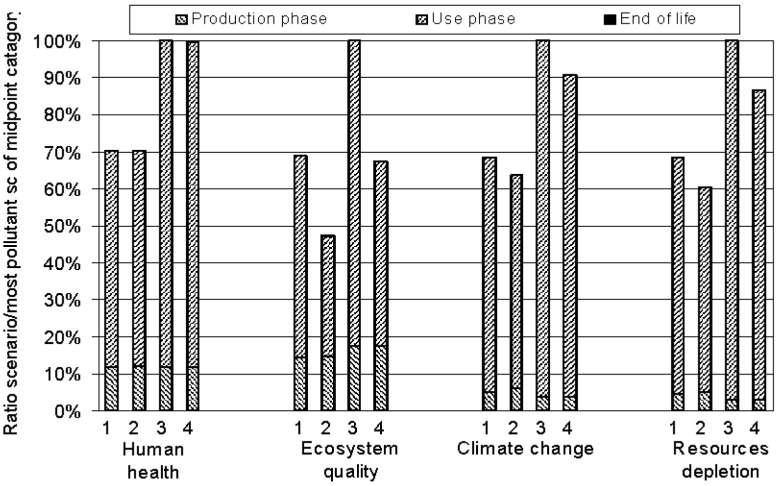

Fig. 9 Comparative 'impact 2002+' damage categories for the full life cycle. scenarios:

1. Korean electricity mix: full composite scenario(landfill end of life)
2. European electricity mix: full composite scenario(landfill end of life)
3. Korean electricity mix: stainless steel scenario(reuse end of life)
4. European electricity mix: stainless steel scenario(reuse end of life)

4. Conclusions

The following principle conclusions can be drawn from this study:

1) For all scenarios, the use phase dominates all environmental impact categories (>80%). However, the production phase is not negligible and could represent 5 to 20%. The end of life phase is negligible in all scenarios, except for the case where aluminium is recycled in the aluminium scenario.

2) To reduce energy consumption in the use phase the rail carriage weight is a key factor to minimise, for example: a weight increase for the car-body of one ton implies an increased energy requirement of 0.0259 kWh/km for this specific regional train. Considering the large amount of energy consumed during the use phase, *the composite scenarios represent a credible option.*

3) The life cycle assessment showed that the full composite scenarios, for both end of life scenarios (land fill and incineration), were the lowest in impact for all midpoint categories.

4) Key impact results for this LCA for steel and full composite variants are shown in Fig. 9 for both the Korean and European electricity mix.

5) Steel scenarios had the lowest performance with the full composite scenarios showing a 30 to 50% improvement. These results strengthen the case for the composite car body options in terms of environmental criteria. The European cases had lower impacts than the Korean cases, except for human health impact (which

was similar), which is explained by the fact that the highest fraction of Korean electricity is produced via coal-fired plants.

References

1. ISO 14040:1997(F), ISO 14041:1998(E), ISO 14042:2000(E), ISO 14043:2000(E).
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