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Smidt Dreijer, Leise; Birkved, Morten; Howard, Thomas J.; Bey, Niki

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The sustainability effects of Product/Service-System design validated through Life Cycle Assessment

Leise Smidt Dreijer
M.Sc. Engineering
Design and Applied
Mechanics
Technical University
of Denmark
leise45@hotmail.com

Associate Professor Morten Birkved, Technical University of Denmark, Denmark, birk@dtu.dk
Associate Professor Thomas Howard, Technical University of Denmark, Denmark, thow@mek.dtu.dk
Associate Professor Niki Bey, Technical University of Denmark, Denmark, niki@dtu.dk

Short Summary

Temporary buildings are generally considered to be unsustainable due to a short life span of the materials applied in the building. The construction materials typically have a longer use life than the required use life of the building, thus functioning building materials are often discarded after the demolition. In an attempt to improve the sustainability of temporary buildings, a Product/Service-System (PSS) strategy is here applied to a case project. The case project concerns a temporary building made of leased materials and building components such as shipping containers, scaffolding materials and lifts. The major research question for the case is how the supplier's continued ownership of the building materials influences the sustainability of such buildings.

By using a PSS design approach in the early design stages, the architects involved in the case project were able to make design decisions based on the whole life cycle of the building components, e.g. design-for-disassembly and design-for-reuse. The lease of materials will ensure that the building materials are re-used at the end-of-life stage. This is expected to prevent production of waste and improve the overall environmental sustainability of the temporary building.

The validation of the improved sustainability of the PSS-based building solution is achieved by comparing the PSS with a corresponding conventional approach for the temporary building through a comparative Life Cycle Assessment (LCA). The results show that over the entire life cycle, the aggregated environmental impact score for the PSS solution is 27% lower than the conventional solution when including operational energy and 37% lower when operational energy is excluded.

Keywords: Product/Service-Systems; temporary buildings; Life Cycle Assessment; closed loop systems; circular economy; life cycle design; waste prevention.

1. Introduction

The manifesto for a circular European Economy was published by the European Commission on the 17th of December 2012. It declares that:

"In a world with growing pressures on resources and the environment, the EU has no choice but to go for the transition to a resource-efficient and ultimately regenerative circular economy. Our future jobs and competitiveness, as a major importer of resources, are dependent on our ability to get

more added value, and achieve overall decoupling, through a systemic change in the use and recovery of resources in the economy". [1]

The building sector creates one third of the total waste production in Denmark [2] and in Europe [3] and represents a challenge in terms of resource consumption and waste handling. At the same time, there is an increasing need for temporary and affordable buildings which can adapt to the changing needs and sizes of companies, municipalities, schools and universities. However, impermanent buildings are generally unsustainable, as the amount of material required is comparable to permanent buildings, though with a much shorter lifespan. As the European Commission declared above, this calls for systemic change in the use of resources. Product/Service-Systems offer such a systemic change, which has the potential to radically reduce the environmental impacts of traditional products. Several studies ([4], [5] and [6]) performing LCAs on various Product/Service-Systems have shown a 30-75% reduction of the environmental impact of Product/Service-Systems compared to the conventional solutions.

This paper presents the business potential for using Product/Service-Systems (PSS) in the building sector and explains how the suppliers extended ownership and responsibility in a PSS can facilitate multiple use cycles of building materials, thereby avoiding useful materials going to waste.

Thereafter, the sustainability effects of a Product/Service-System will be quantified using LCA. An LCA has been carried out on a case study in order to investigate how a PSS solution can alter the environmental profile of temporary buildings.

2. Product/Service-Systems in the building sector

2.1 Introduction to Product/Service-Systems

Product/Service-Systems (PSS) have already entered the building sector through lighting services (e.g. Philips), furniture services (e.g. Gispen, the Netherlands) and carpet leasing programmes (such as Interface Inc, USA) [7]. Here, the customer pays for the function, e.g. square meter carpet per year, rather than for the product which delivers the function, e.g. the carpet itself. The company installs, monitors, maintains and replaces the carpets whenever necessary, making it convenient for the customer.

Product/Service-Systems have similarities with circular economy, where resources are kept and restored in closed loops, belonging to either the technosphere or ecosphere. They also have parallels with approaches such as Service Economy and Functional Economy, where the object of sale is a performance, customer satisfaction or result, in contrast to industrial economy, where the object of sale is a product [8].

Here we will offer two general definitions of PSS, the first relating to what it is, and the second to how it can be achieved.

"A marketable set of products and services capable of jointly fulfilling a users/customers need in an economical and sustainable manner." [9]

"PSS strategy is to shift from business based on the value of the exchange of ownership and responsibility, to business based on the value of supporting and enhancing the utility of products throughout their entire life cycle." [10]

This paper will apply both definitions to construction materials and quantitatively as well as qualitatively assess the sustainability of Product/Service-Systems in the building industry.

2.2 PSS business case for construction materials

Currently, most construction material suppliers work with a simple point-of-sale model, where the ownership and responsibilities are transferred to the customer. A Product/Service-System extends the ownership and responsibility of the supplier to the entire life cycle [8], i.e. in our case to the entire life cycle of the temporary building. Thereby, the supplier sells the right to use the material, rather than the material itself, typically through a lease agreement. The PSS may also include servicing and repair of the construction components during use. After use, the manufacturer will take back the product and re-use or recycle it. The customer gets what he wants; the ability to use materials in the form of a building for a certain amount of time, and avoids the usual hassle of being in charge when something breaks down as well as having to cover the expenses for disposal of materials at the end-of-life.

Product/Service-Systems thus provide opportunities for entirely new business models in the construction industry. Lease agreements give economic benefits for both the supplier and the contractor; they give a sustained income for the supplier and improve the cash flow of the developer. The supplier keeps a ‘material bank’ at his customers, which later can be used as feedstock in the production, making him more resilient to fluctuating market prices and resource scarcity.

There are thus strong economic incentives on both the supply and demand side for Product/Service-Systems. However, it should be considered whether PSS solutions also are environmentally beneficial.

2.3 Product/Service-Systems and sustainability

Mark Goedkoop et. al. [9] found that although a shift from a product to a service is, on average, environmentally sound, there are exceptions with high variability. Therefore they recommend assessing the sustainability of Product/Service-Systems case by case.

Several studies on the sustainability effects of various Product/Service-Systems have previously been carried out. A study of a bicycle sharing system [4] found that the total environmental impacts could be reduced by 30% through improved robustness of the bicycles and that a 45% reduction could be achieved through improved maintenance service. A similar study [5] comparing a PSS self-service laundry system with household washing machines found that the carbon emissions could be reduced by more than 50% through optimised utility of the washing machines. Another study of the leasing of water filtration devices [6] concluded that a reduction of 75% of the total environmental impact over a 4 year lifespan could be obtained through maintenance, increased lifespan and improved end-of-life treatment.

In these studies, several features of Product/Service-Systems were identified as factors to improve sustainability:

- Longer lifetimes through robustness and maintenance
- Optimised utility of products through leasing and sharing
- Improved end-of-life treatment.

All of these features can be relevant in a Product/Service-System of construction materials. However, this case project has focused on optimised utility through leasing and improved end-of-life treatment. In order to achieve optimised utility and improved end-of-life treatment of construction materials, the Product/Service-System design may take its starting point in a cyclic material model, as first suggested by the Swiss architect Walter R. Stahel in 1982 [11]. His self-replenishing model recommends choosing reuse over repair, repair over reconditioning and reconditioning over recycling. Incineration and landfill are not at all included in his model, and should be excluded from PSS models since recycling is generally preferable to these options [12].

Whether a given PSS is sustainable is thus a question of its design. As PSSs focus on the value of use rather than the value of ownership, they render planned obsolescence obsolete and instead promote durable design. They extend the responsibilities of the producer and thereby align the producer interests with the interests of the consumer. Product/Service-Systems may thus be an important step in the transition from a ‘buy-and-throw-away’ consumption culture, to a system where the utility of products is optimised, equitably distributed and environmental resources carefully managed.

3. Case study and environmental impacts

3.1 Measuring the environmental effect of PSS through LCA

This paper seeks to go beyond conventional eco-design, and focus on the sustainability effects of the Product/Service-System. Thus, the focus is not so much put on choice of materials, but on the effect of making re-use an intrinsic part of the system surrounding the building.

LCA is suitable for assessing the environmental impacts of both products and services, as these can be compared on the basis of the same functional unit [13]. That allows us to compare leased and bought materials in this case. The LCA was carried out according to the ILCD recommendations and EN15978:2011 standards for environmental assessment of buildings.

3.2 Introduction to the case study

This study is based on a temporary building designed by Lendager Arkitekter, a Danish architect studio which is specialised within sustainable design. The building consists of components and materials that are either leased or bought on take-back contracts between the developer and suppliers. In these contracts, the suppliers guarantee taking back the materials after use, which ensures re-use of functional materials.

The building itself is designed for assembly, disassembly and re-use of the materials. The dimensions of the leased materials determine the dimensions of the construction, rather than fitting the materials to the design. Thereby construction waste is reduced significantly, and the materials can be re-used directly after the use phase. The materials chosen for the building are materials which are traditionally leased for other purposes. They include shipping containers, scaffolding materials, lifts and pre-fitted bathroom containers. The containers are used as building blocks to form the outer wall of the building. The resulting modular design makes it possible to modify the layout and size of the building during operation, according to the changing needs of the tenants.

Fig. 1: The case study building ‘Eco-Box’

This building is seen as a pilot project for use of Product/Service-Systems in the building industry. The concept behind the building is to lease all construction materials, functions and furnishings, thereby avoiding the creation of waste. However, working within the current network of suppliers, it has not been possible to lease the insulation, wall lining, windows and doors. As the building is still in the design phase and planning stage, the PSS solution focuses on the overall leasing of construction materials, and not on functions such as lighting and furnishing.

3.3 Compared scenarios

The Product/Service-System scenario of re-used and re-usable materials is compared to the conventional scenario of applying first-use materials which receive conventional Danish end-of-life treatment, see table 1. In other words, the LCA compares a model with multiple use cycles of materials with a model with only one use cycle of the materials.

3.3.1 The European waste hierarchy

The European hierarchy prioritises five different waste options, see figure 2 [14]. Out of these five options, the preferred one is waste prevention. The waste prevention strategy has been followed in the design phase of the building under study by reducing the amount of materials per square meter office space and choosing environmentally friendly building materials over materials containing hazardous substances.

Fig. 2: European waste hierarchy [14]

The end-of-life of materials are on average placed higher in the waste hierarchy for the PSS solution compared to conventional Danish building waste treatment, as many materials are re-used rather than recycled. Table 1 shows the construction materials divided into the four waste scenarios; prepare for re-use, recycling, recovery and disposal.

Table 1: Comparison of end-of-life treatment for the two scenarios

Waste treatment	PSS	Conventional
Prepare for re-use	Containers Steel foundation Scaffolding HVAC elements Lift	-
Recycling	Plastics Gypsum Wood based materials Windows and doors Fibre cement Staircases and bridges Screws, bolts and nails	Containers Steel foundation Scaffolding Windows and doors Staircases and bridges HVAC elements Wood based materials Plastics Gypsum Screws, bolts and nails Lift
Recovery (energy recovery rate >60%)	Bitumen Cellulose insulation UPM flooring Roof cover	Bitumen Cellulose insulation UPM flooring Roof cover
Disposal (energy recovery rate <60%)	-	-

In 2009, 5 mio tonnes of building waste was produced in Denmark, this equalled more than one third of the total waste production. 96% of the total mass of building waste was recycled. However, most of this recycled material is dirt, stone, concrete and asphalt which is crunched and used as roadfill [1]. This can be considered ‘downcycling’ rather than ‘recycling’. This means that there are still improvements to be made in the treatment and utility of building waste, improvements which are often intrinsic in Product/Service-Systems.

3.4 Goal and Scope

3.4.1 Goal

The goal of this LCA is to quantify the environmental improvement originating from Product/Service-Systems of building materials and components.

3.4.2 Functional unit, reference flow and key parameters

The PSS and conventional solutions are compared on the basis of the functional unit:

Providing 790 m^2 office space in Denmark for 8 years (2013-2021) including heating, ventilation and cooling according to Danish energy requirements for 2015.

The reference flow is one building and its energy consumption during use. The key parameters are the amount of materials per square meter office space and use life of construction materials.

3.4.3 Modelling framework and handling of re-use and recycling of materials

The modelling of the end-of-life is done by system expansion and subtraction using average data according to the ILCD handbook (situation A) [15] and the EN 15978:2011 standards [16].

The recovered energy resulting from incineration of the materials is assumed to substitute average electricity in the Danish grid.

For recycling, the net impact of the building material is calculated as the impacts related to the recycling process minus the impacts from producing the substituted product. The substituted product is the average market mix, in accordance with the recommendations of the ILCD handbook [15].

The modelling of re-used materials is relevant in this case, as the use life of the materials is longer than the required use life of the building. Reused and reusable materials are however not environmentally 'free' due to wear during use. The total impacts related to the production stage and end-of-life of the component must therefore be allocated to the different use cycles. The allocation is done according to ILCD's recommendations for handling of re-used materials in attributional LCAs, and the chosen allocation factor is based on time.

The allocation factor is the ratio between the required use life of the building (RULB) and the expected use life of the materials (EULM), where RULB < EULM.

For leased materials, the economic and time-based allocation factors are equivalent, as the monthly payment does not depend on the former use period of the materials. In a Product/Service-System, the customer pays according to functionality of the solution, not according to the newness of the materials. At the end of the materials' use life, the entire production and end-of-life processing is accounted for by the sum of use cycles.

3.4.4 System boundaries

The LCA covers the whole life cycle of the building, from raw material extraction to end-of-life or 'end-of-cycle'. The included life cycle stages are shown in table 2.

Table 2: Life cycle stages in the LCA

Stage	Unit process
Production stage	Raw material supply Transport to manufacturer Manufacturing
Use stage	Replacement of components Operational energy use
End-of-life	Waste processing Disposal
Next product system	Reuse, recovery or recycling potential

The surrounding outdoor grounds and materials for plumbing, furnishing, electrical installations and lighting are outside the system boundaries.

3.5 Life cycle inventory

In the production stage, primary data from suppliers was used to set up the life cycle inventory of materials. The inventory was modelled in the LCA tool GaBi (version 4.4) with EcoInvent (version 2) datasets using fully parameterised modelling. The production stage of all construction materials were modelled and divided into six building elements to allow a better overview of the building:

1) Building base (including leased containers and point foundations)
2) External walls (no leased materials)
3) Internal walls (no leased materials)
4) Ceilings, floors, stairs and balcony (including leased scaffolding and lift)
5) Roofs (including leased scaffolding and cover)
6) Central energy, heating and cooling units (including leased HVAC elements)

For the replacement stage and for allocation of re-used materials, the expected lifetimes of materials and components were collected directly from suppliers. The operational energy was calculated as a function of floor area using the Danish 2015 energy requirements for office buildings. The import of electricity was modelled using average Danish grid mix. The waste processing and recycling was modelled manually with data from EcoInvent datasets and WRAP 2010 [12] data for plastics. The recycling processes are assumed to be 90% effective. BUWAL datasets were applied for the energy recovery of different materials.

3.6 Life cycle impact assessment methodology

ReCiPe version 1.0 was applied in this case, and all 18 midpoint categories and 3 endpoint categories were calculated using the Hierarchist characterisation and normalisation factors. The characterised impact categories are extracted at midpoint, translated to endpoint, then normalised and weighted at endpoint using average ReCiPe weighting factors [17]. The weighted endpoints are then aggregated to a single score on which the different alternatives are compared.

3.7 Life cycle impact assessment results

3.7.1 Production stage

Quantified in dimensionless weighted endpoint scores, the total impacts related to the production are 27% lower for the PSS solution than for the conventional solution due to the use of re-used materials. The leased materials currently make up 65% of the total mass of the building. Therefore, a greater reduction could potentially be achieved if an even higher ratio of the materials could be leased.

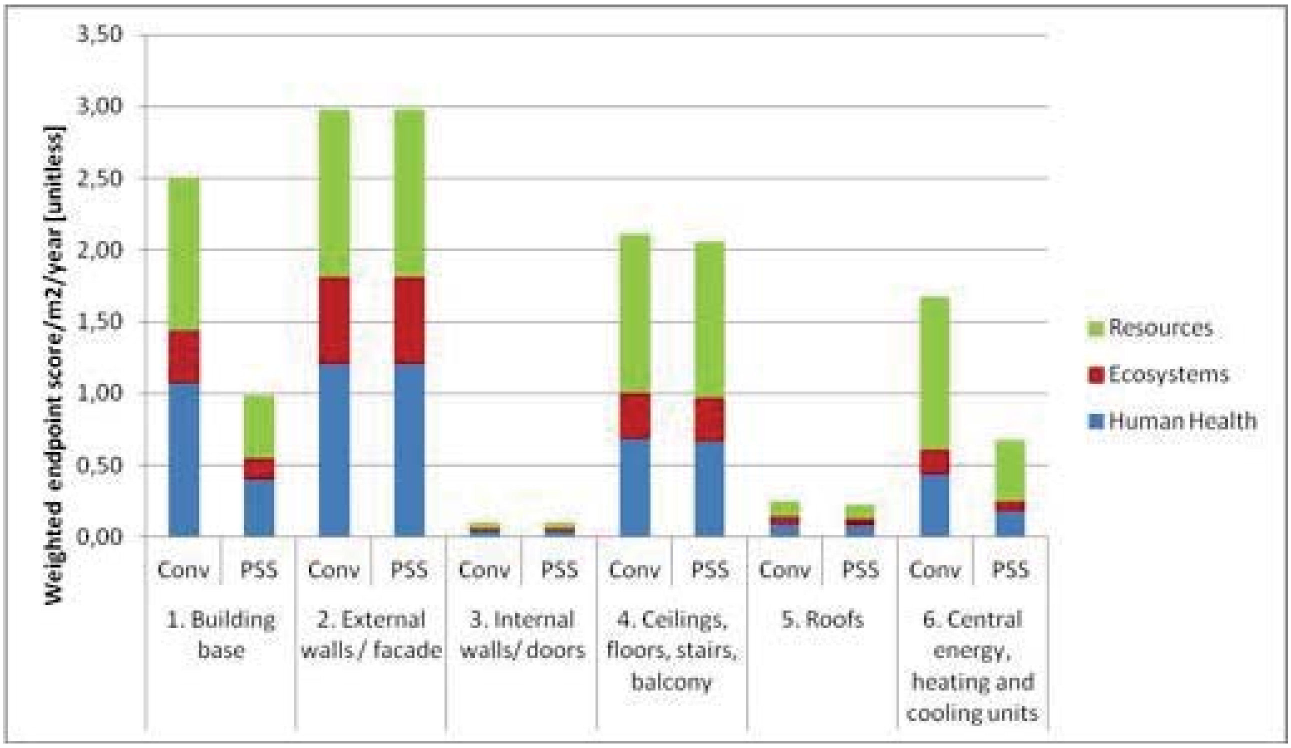

Fig. 2: Weighted endpoint scores for building materials of conventional and Product/Service-System solutions

Figure 2 compares the conventional solution with a Product/Service-System building using the same materials split into six building elements. The largest difference can be found in the building base, which consists of leased containers and leased point foundations. Here, the PSS components only amount to 39 % of the conventional solution quantified in dimensionless weighted endpoint scores - a reduction of 61%. The internal and external walls consist of wood, plastic, windows and insulation, which are currently not offered by a Product/ Service-System. Therefore, the impact here is the same for the two solutions. Building elements 4, 5 and 6 specified in figure 2 consist of a mix of re-used and new materials; therefore the PSS solution's potential impact is slightly lower than the conventional solution.

3.7.2 Use stage

Figure 3 shows the potential life cycle impacts divided into five stages. The operational energy consumption is the same for the two solutions. This stage corresponds to 26% of the total life cycle impact for the conventional solution, and 36% for the PSS solution which has lower impacts in other stages. This is relatively low due to the short life span of the temporary building. There is however great uncertainty related to the amount of operational energy required, as no energy calculation has yet been performed on the building. The impacts here are also highly dependent on the composition of energy sources in the grid.
In the replacement stage only the roof cover is replaced due to the short life time of the building. Therefore, the replacement stage only contributes with 1% to the total life cycle impacts.

3.7.3 End-of-life

For the end-of-life processing, the environmental impact score of the PSS solution is 52% lower than the conventional solution. This is significantly more than the reduction at the production stage. This is caused by the energy demanding process of smelting steel and aluminium, which also contribute highly to the endpoint impact 'Resources'. The roof cover containing PVC and cellulose insulation containing boric acid are incinerated rather than re-used at end-of-life. These materials contribute highly to eco-toxicity. It can therefore be argued that improvement at end-of-life could be obtained by replacing these materials by non-toxic ones, in an eco-design approach.

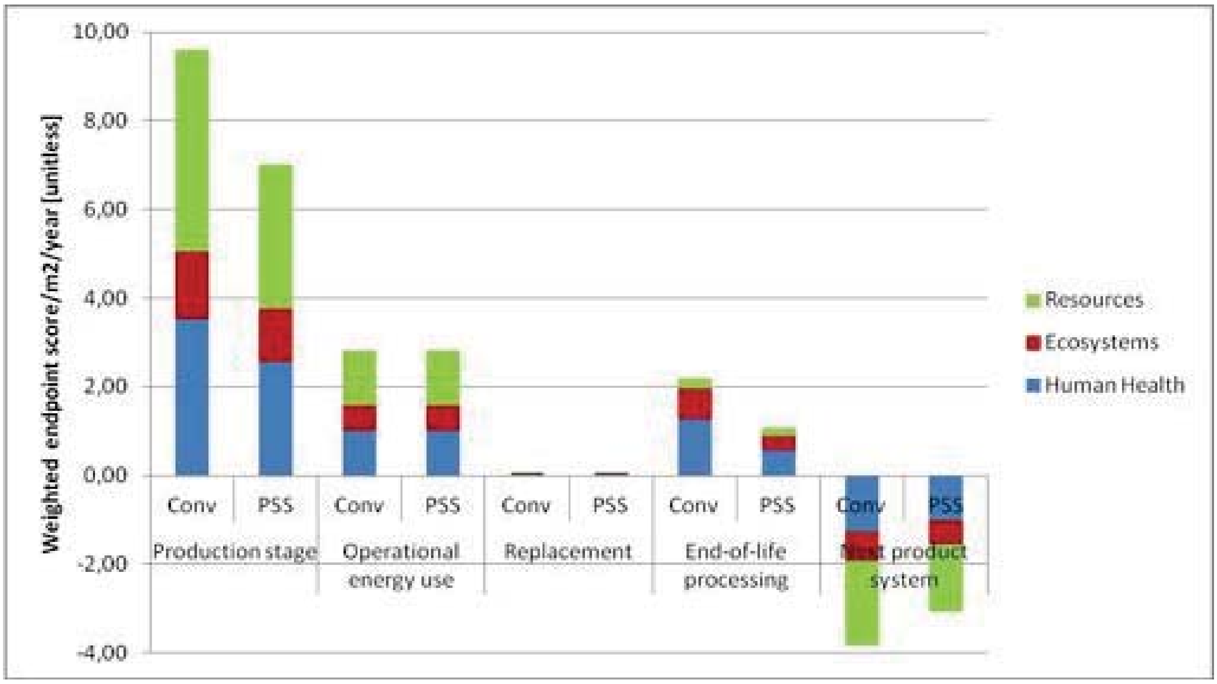

Fig. 3: Weighted endpoint scores for the full life cycle of the conventional solution and PSS

The fact that the end-of-life processing is significantly lower for re-use compared to recycling is another reason to extend the total use life of components through Product/Service-Systems, thereby postponing recycling of the material and lowering the impact per use.

3.7.4 Total life cycle

Over the entire life cycle, the aggregated environmental impact score for the PSS solution is 27% lower than the conventional solution when including operational energy and 37% lower when operational energy is excluded.

3.7.5 Sensitivity analysis

A sensitivity analysis was performed by varying the input parameters by 10% and calculating the corresponding change in total output. The sensitivity analysis showed that all of the input parameters has a sensitivity ratio (percentage change in input divided by percentage change in output) of below 0.01, and can therefore be characterised as having low sensitivity. This means that a change in individual parameters will not have a significant effect on the result.

4. Conclusions

4.1 Discussion

A barrier to using Product/Service-Systems in the building sector today is that the materials cannot be modified. Customisation of leased materials to meet many different needs and building designs represent a challenge for both architects and material suppliers. Also, the limited choice of materials which can be leased today may result in bulkier designs, which eventually use more resources despite re-use. In this case, the shipping containers may be much larger and heavier than alternative materials necessary to create the building structure. Thus, the total material consumption and type of material should be taken into consideration when designing buildings based on Product/Service-Systems.

Furthermore, the rebound effect should be avoided, so that the higher affordability of impermanent buildings through Product/Service-Systems does not lead to increased use of resources on the whole. Although the temporary building can be built and run with 27% less potential environmental impacts through Product/Service-Systems, permanent buildings may on average remain more sustainable than temporary buildings. This is due to the added impacts of transport, construction and deconstruction in temporary buildings. A PSS model may not be suitable for permanent buildings, as the lease period can be too long and therefore the risk too great. Only 65% of materials can be leased in this case example, as materials which are too fragile to be mounted and de-mounted several times cannot be leased. A Product/Service-System based on leasing entire module-based buildings would ensure re-use of all building materials.

4.2 Conclusion

Product/Service-Systems push the benchmark for lifetimes and end-of-life treatment of materials, and thereby reduce the total environmental impact. It was shown that Product/Service-Systems can potentially improve the environmental sustainability of single building components used in temporary buildings radically, in our case example up to 85%. The improvement rate depends on the lifetime of the component versus the lifetime of the building. In general, the shorter the lifespan of the building or the greater the uncertainty of the building's future, the more environmentally beneficial the PSS solution will be.

Since not all the building materials can be leased in this case, the leased materials must be supplemented to form a functioning building, and this affects the total environmental sustainability of the building negatively. Thus over the entire life cycle, the aggregated environmental score for the PSS solution is 27% lower than the conventional solution. The overall reduction of impacts in the production stage is 27% in this case study. The total environmental impact score related to the end-of-life processing is reduced by 52% in the PSS solution, due to avoided energy-heavy recycling of metals. The operational energy only amounts to 26% of the total impacts of the temporary building. This underlines the importance of improving the sustainability of materials used in temporary buildings, by e.g. leasing materials through Product/Service-Systems.

4.3 Further work

Further research on PSS in relation to this case was carried out in this project. A main goal was to compare the environmental life cycle assessment with a life cycle costing model on the same case, in order to find environmental and economic trade-offs and synergies of Product/Service-Systems. Also, further work can be done on how much a PSS and an Eco-design approach respectively can contribute to reducing the environmental impacts in the building sector.

4.4 Acknowledgements

We would like to thank Lendager Arkitekter and Design City Kolding for providing the case on which this paper is based.

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